THE ROLE OF NEUROMUSCULAR PERFORMANCE ON BONE STRENGTH AND PROPERTIES IN THE FOREARM AND LOWER LEG OF CHILDREN

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By

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ABSTRACT

Introduction: The role of muscle forces in determining bone micro-architecture and strength in children is poorly understood as limited evidence relies on surrogate measures of muscle force such as muscle size. The objective of this thesis was to explore the role of muscle area, peak forces from neuromuscular performance tests and physical activity in determining bone properties at the radius and tibia in children.

Methods: 37 boys and 42 girls (mean age 10.5; SD 1.6y) had their dominant forearm and lower leg imaged using peripheral quantitative computed tomography (pQCT) and high resolution pQCT (HR-pQCT). Bone mass, density, area and estimated strength were assessed. Muscle area was determined from the pQCT scans and grip strength measured via a handheld dynamometer. Peak force from a single maximal push-up performed on force platforms and the number of standard push-ups completed in a single attempt were recorded. Countermovement and standing long jump maximal forces were recorded, impulse and power were calculated, and average standing long jump distance was measured. Physical activity was measured using the Physical Activity Questionnaire for Children. Sex, maturation (estimated age from peak height velocity), weight and limb length (ulna and tibia) were controlled in the linear regression models. Variance predicted (R^2) by models using muscle area, neuromuscular performance measures as independent predictors (squared partial r) of bone properties are reported.

Results: Grip strength and muscle area independently predicted 14-18% of the variance in bone area at the distal radius and 9-22% of the variance in bone strength at the distal and shaft sites of radius. Peak push-up force predicted 10% of the variance in trabecular number at the distal radius. Muscle area independently predicted 5-28% and

countermovement and standing long jump forces and impulses predicted 6-10% of the variance in bone area, cortical content or density at the tibia shaft. Standing long jump power predicted 5-8% of the variance in bone area and cortical density at the tibia shaft. Physical activity predicted 9% of the variance in trabecular number at the distal tibia.

Discussion: Thesis findings support the use of muscle area as a surrogate for muscle forces and identified neuromuscular performance measures that will guide targeted exercise interventions aiming to optimize bone strength development in children.

ACKNOWLEDGEMENTS

"My mother drew a distinction between achievement and success. She said that achievement is the knowledge that you have studied and worked hard and done the best that is in you. Success is being praised by others. That is nice but not as important or satisfying. Always aim for achievement and forget about success."

Helen Hayes ~Actress (1900-1993)

Writing a Master's Thesis was not something I had ever planned on or thought I was ready for, but somehow it has managed to become one of my greatest accomplishments. There are so many people who have helped me progress through this challenge and to thank them all would take more pages than the length of this thesis. For those of you I neglect to mention please do not think I have forgotten, you were all important parts in this journey and this milestone achievement.

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PREFACE

Sections of this thesis have been presented as multi-authored presentations at conferences locally and internationally. The research was performed by me except for the image acquisition (both pQCT and HR-pQCT), which was carried out by two imaging technicians (Graduate Students). Data analyses and presentation preparation were carried out by me and the co-authors contributed in the editing of submitted abstracts, presented posters and podium presentations.

1. **Kelsey Björkman**, Joel Lanovaz, Saija Kontulainen. Role of muscle area, grip strength and neuromuscular performance in predicting radius bone strength at the wrist and forearm in children. Bone and Joint Imaging Group Knowledge Transfer Conference, Podium presentation January 2014

2. **Kelsey Björkman**, Joel Lanovaz, Chantal Kawalilak, JD Johnston, Saija Kontulainen Role of muscle area, grip strength and neuromuscular performance in predicting radius bone properties and strength at the wrist and forearm in children. Life and Health Sciences Research Day, Poster presentation March 2014

3. **Kelsey Björkman**, Andrew Frank-Wilson, Whitney Duff, Saija Kontulainen. Precision of pQCT measurements of muscle area, density and subcutaneous fat in children. Life and Health Sciences Research Day, Poster presentation March 2015

4. **Kelsey Björkman**, Joel Lanovaz, Whitney Duff, Chantal Kawalilak, JD Johnston, Saija Kontulainen. The role of muscle area, grip strength, and neuromuscular

performance in predicting radius bone strength at the wrist and forearm in children. Pediatric Child Health Trainee Research Day, Podium presentation April 2015

5. **Kelsey Björkman**, Joel Lanovaz, Whitney Duff, Chantal Kawalilak, JD Johnston, Saija Kontulainen. Role of Muscle Area, Grip Strength, Physical Activity, and Neuromuscular Performance in Predicting Bone Area, Micro-Architecture and Density at the Distal Radius and Tibia in Children. 3rd Annual XtremeCT Users Meeting, Podium presentation October 2015

Authors' contribution for all presentations involved: Kelsey Björkman was responsible for coordinating the study, conducting the force data collection, image and force data processing, data analyses, and writing and editing of the original abstracts, posters and presentations. Dr. Saija Kontulainen was jointly responsible for the original ideas, supervision, and editing the abstracts, posters and presentations. Dr. Joel Lanovaz was jointly responsible for supervision, editing the abstracts, posters and presentations, and wholly created the MatLab processing scripts. Whitney Duff was responsible for pQCT image acquisition and editing the abstracts, posters and presentations. Chantal Kawalilak was responsible for HR-pQCT image acquisition and editing the abstracts, posters and presentations. Andrew Frank-Wilson was responsible for the training on, and use of, the ImageJ programming, and editing the abstracts, posters and presentations. Dr. J.D. Johnston was responsible for editing the abstracts, posters and presentations.

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GLOSSARY

TERMS	DEFINITION
Anisotropic	Refers to being directionally dependent; (e.g., a rectangle is anisotropic, not all side lengths are equal)
Areal bone mineral density	Imaging measure of bone mineral content / image area (g/cm^2) as measured by DXA
Bone Density	General term referring to the mass of a bone within a specified volume or area. Refers to apparent bone mineral density, areal bone mineral density and volumetric bone mineral density
Cancellous	Type of bone tissue comprised of vertical and horizontal trabeculae which create a spongy, cellular-like tissue; typically occurs at the end of long bones; synonymous with trabecular bone
Compact bone	Type of bone tissue comprised of multiple layers of compacted bone; forms the cortex or outer shell of bone; much denser and stiffer than cancellous bone; synonymous with cortical bone
Cortical bone	Type of bone tissue comprised of multiple layers of compacted bone; forms the cortex or outer shell of bone; much denser and stiffer than cancellous bone; synonymous with compact bone
Distal	Pertains to the end of an extremity; distal end of extremity is the end situated farthest from the center of the body (e.g., distal tibia is located at ankle joint)
Ex vivo	Latin for "out of the living"; experimentation using tissue from an organism in an external environment
In vivo	Latin for "within the living"; experimentation using a whole, living organism as opposed to partial or dead organism

Isotropic	Refers to uniformity in all directions; (e.g., a square is isotropic, all side lengths are the same)
Medial	Situated at or extending to the middle
Peak height velocity	Refers to the age at which a participant experiences the fastest rate of growth
Proximal	Pertains to the end of an extremity; proximal end of extremity is the end situated nearest the center of the body (e.g., proximal tibia is located at the knee joint)
Trabeculae	Latin for "small beam"; bone tissue element in the form of a small beam, strut or rod
Trabecular bone	Type of bone tissue comprised of vertical and horizontal trabeculae which create a spongy, cellular-like tissue; typically occurs at the end of long bones; synonymous with cancellous bone
Volumetric bone mineral density	Imaging measure of bone mineral content / image volume (g/cm^3) as a measure by QCT
Voxel	Refers to a volume element; typically represented by a picture element, or pixel, in a QCT image; images from pQCT and HR-pQCT use voxels

ABBREVIATION	DEFINITION
2D	Two dimensional
3D	Three dimensional
aBMD	2D areal bone mineral density (mg/cm^2); DXA measure
BMC	Bone mineral content (mg)
BMD	Apparent bone mineral density
BMU	Basic multicellular unit
BSIc	Compressive bone strength index
CMJ	Countermovement jump
CV%	Percentage coefficient of variation
DEXA	Dual energy x-ray absorptiometry, same as DXA
DXA	Dual energy x-ray absorptiometry, same as DEXA
GS	Grip Strength
HA	Hydroxyapatite
HR-pQCT	High resolution peripheral quantitative computed tomography
LJ	Standing Long jump
MuA	Muscle area
PAQ-C	Physical Activity Questionnaire for Children
PHV	Peak height velocity
pQCT	Peripheral quantitative computed tomography
RCT	Randomized Control Trial
ROI	Region of interest
SSIp	Polar stress-strain index
vBMD	3D volumetric bone mineral density (mg/cm^3); QCT measure

INTRODUCTION

Optimizing bone strength in children may help to reduce fracture risk both in childhood and later in life (Kontulainen et al., 2013). The origins of skeletal fragility and osteoporotic fracture risk have been linked to skeletal growth (Cooper et al., 2006), as the majority of bone growth occurs during the maturation process and adolescence (Bailey et al., 1999). It has also been shown that participating in (whole body) physical activity (e.g. gymnastics, wrestling) as a child is associated with better bone strength as an adult (Farr, 2006; Erlandson et al. 2012, Nilsson et al., 2009; Duckham et al., 2014). Therefore, in order to improve bone strength later in life, improvements in bone strength during the peak bone growth period (childhood and adolescents) should be optimal.

In 1987, Harold Frost proposed a model that bone tissue adapts to external forces placed on it (Frost, 1987). His model, “mechanostat”, indicated that mechanical influences (or lack there of) can affect bone architecture (Frost, 1987). Whether those mechanical influences were from every day loading through ground reaction forces of physical activity, or from forces acting on bone from muscular contractions, bone would adapt its physical geometry in order to maintain a stable state. The mechanostat model also works in reverse in that if a bone is not being loaded frequently enough to require excess strength, it would adapt in a reverse manner becoming weaker.

Bone is a metabolically active tissue which dynamically alters its structure to meet the demand placed on it by muscle forces and loads created by gravity to resist fracture

(Dempster, 2006). It has been shown that bones of the lower limbs (tibia) will adapt to an increased loading stimulus over a short period of time (Macdonald et al, 2007), and that the majority of the loading stimulus on the bones in the upper extremities are caused by muscle contractions (Földhazy et al., 2005). Bone strength in the growing skeleton has been positively associated with the strength and size of muscles (Kontulainen, Sievanen, Kannus, Pasanen, & Vuori, 2002; Macdonald et al., 2005; Macdonald, Kontulainen, Petit, Janssen, & McKay, 2006; Schoenau, Neu, Beck, Manz, & Rauch, 2002; Schoenau, Neu, & Manz, 2004); however, there is minimal research that shows what types of physical activities produce the best loading stimulus for increasing and maintaining bone strength, especially in the upper extremities of children.

Muscle forces acting on bone are a key component in the maintenance of bone strength as bones that are not loaded directly through ground reaction forces are mainly loaded through the muscle bone interaction. A problem can arise when a stable state is not maintained and bones decrease in strength as a result of decreased bone loading. A decrease in bone strength may increase the risk of fracture, while a decrease in physical activity may be linked to suboptimal development of cortical bone thickness (Cain et al., 2013; Kontulainen et al., 2013). Lack of activities which specifically load the forearm through muscular contraction may result in the suboptimal development of bone in the forearm (Kontulainen et al., 2013).

Bones of the lower limbs are dually loaded; naturally by body weight and ground reaction forces during daily physical activity and by forces produced through muscle contractions.

Lower leg bones pose less of a risk for fracture than that of their upper body counterpart (Nishiyama et al., 2011). In contrast, arms are not frequently loaded by ground reaction forces and are mainly loaded by muscle contractions. As such, they do not experience the same loading as the legs. Physical activities that utilize the whole body are important in loading both the upper and lower limbs to maintain and improve bone strength. Although there has been some research that studied the effects of impact loading on the lower limbs (Macdonald et al. 2006; Macdonald et al. 2007) of children, further evidence of neuromuscular performance associated with bone microarchitecture and strength in children is needed. In addition, research is lacking regarding the effects of loading on the upper limbs, and what activities optimally enhance bone strength. The effect of exercise to optimize bone structure and strength development during growth is poorly understood and evidence relies on a few randomized control trials (RCTs) (Macdonald et al., 2007; Kontulainen et al. 2013; Farr, 2006; Nikander et al., 2010; Tan et al., 2014). This lack of research is especially prominent in children, even though the window of opportunity to optimize bone development is during the peak height velocity growth period in childhood and adolescence, (Farr, 2006; Kontulainen et al., 2013, Bailey et al., 1999). Associations between neuromuscular performance and bone strength have been shown in the lower limbs of adults (Rantalainen et al,. 2010; Nikander et al., 2010), however, this has not been shown in children. Information regarding the associations between neuromuscular performance and bone properties site-specifically will help in the development of strategies and interventions aiming to optimize bone strength and improve fracture prevention. If a specific physical activity or neuromuscular performance measure is found to be associated with bone strength, interventions could use that specific loading modality to optimize bone strength in the lower leg and fracture-prone forearm in children.

Optimising bone strength during peak pubertal growth is an important factor in reducing fracture risk and skeletal fragility (Cooper et al., 2006; Kontulainen at al 2013). Explained by Wolff's Law (1897) and Harold Frost's Mechanostat (1987), mechanically loading bone through ground reaction forces or muscle contractions is an important part of maintaining and improving bone strength. Limited evidence relating neuromuscular performance to bone strength pertains to children (Macdonald et al., 2006), and has not included the fracture-prone forearm. Therefore, the overall aim of this thesis was to explore associations between neuromuscular performance and bone properties (e.g. size, structure, mass, density) and bone strength to assist in the design of interventions to optimize bone strength development in children.

1.0 BACKGROUND LITERATURE

The scope of this thesis is mainly focused on the association between neuromuscular performance and bone properties and strength in the lower leg and forearm of children. A small amount of background information is needed to set the stage of this study. This literature review will summarize the background information regarding the key concepts of bone physiology, strength, and adaptation, as well as information pertaining to the measurement of such things. It also provides earlier evidence linking muscle, neuromuscular performance, and bone structure and estimated strength.

1.1 Bone Physiology and Anatomy

Bone is a metabolically active tissue that is constantly adapting (modeling and remodeling) to the environment and loads (or stresses) placed on it by external sources (Dempster, 2006). Muscle forces, along with gravity, are the main sources of loading placed on bone (Dempster, 2006; Macdonald et al., 2005; Lanyon, 1992; Földhazy, 2007). In addition to the structural support bone provides the body, bone functions as a mineral trap, and as a protective barrier for vital organs (Dempster, 2006). Bone needs to be flexible and strong enough to resist fracture during torsion, compression, and bending. As well, it needs to be stiff enough to resist deformation and support the weight of the body and light enough to be moved in an efficient manner. Its material composition reflects this. Crystalline calcium hydroxyapatite, or HA, is the main inorganic compound found in bone (Robey & Boskey, 2006) and is what forms the structural base of bone, giving it its resistance to compressive loading. Bones get their resistance to tensile and shear loading from type I collagen woven throughout the HA (Rubin & Rubin, 2006).

There are many anatomical types of bones including flat (e.g. ilium, sternum), sesamoid (e.g. patella), long (e.g. tibia, radius), and irregular (vertebrae) bones. Because the long bones in the forearm are the site of the most common type of pediatric fractures in both sexes (Landin, 1997; Bailey et al. 1989), the bones of most concern for this thesis are long bones. Long bones are made up of two types of bone; cortical compact bone and trabecular cancellous bone. The shaft of the long bone is essentially a hollow tube that is made of cortical bone, while the ends of the bone are made up of trabecular bone surrounded by a thin shell of dense cortical bone (Dempster, 2006).

1.1.1 Bone Modeling and Remodeling

Bone modeling is a process by which the bone alters its size and shape in order to adapt to the physical load being placed on it (Forwood, Owan, Takano, & Turner, 1996) and is different from bone remodeling where basic multicellular units replace old bone with new bone, thereby maintaining mass and strength (Karsenty & Elefteriou, 2008). The majority of bone modeling occurs during the growth period in adolescents and declines as a child reaches their full skeletal size. Modeling and remodeling occur as a response to mechanical (loading) influences (Sims & Gooi, 2008). The remodeling process, however, does not occur at just one location or time, but rather at many small sites throughout the skeleton. Sims and Gooi (2008) describe the dynamic “coupled” process of bone remodeling simply as the “coordinated actions of osteoclasts (cells that resorb bone) and osteoblasts (cells that form bone).” Parfitt (1979) names the three stages of the remodeling process as activation, resorption, and formation. Activation is the call for repair or remodeling responded to by the formation of osteoclasts. Resorption is the action taken by the osteoclasts, removing the bone from the repair location. Formation is the building of new bone by the osteoblasts. The coordinated actions of the osteoclasts and osteoblasts during the three stages of the remodeling process are referred to as the Basic Multicellular Unit (Sims & Gooi, 2008). The rate of the osteoclasts removing bone and the osteoblasts building bone, called coupling, changes with age (Lips et al., 1978). Later in life, osteoclast activity (removing bone) outweighs osteoblast activity (building bone), which explains bone loss; however, in childhood osteoblast activity is greater than that of osteoclast activity, allowing for increase in bone mass (Lips, 1978). This leads to the idea that the optimal time to enhance bone strength is during the greatest growth period (Bailey et al., 1999). Both modeling and remodeling effect bone during the growth period. The modeling that bone undergoes during growth is necessary in order to change its cross-sectional size and geometry (Sims & Gooi, 2008). The remodeling that bone undergoes is necessary in order to build more bone and repair any bone that is damaged. Bone needs to retain its strength, but is not meant to be heavy (Macdonald et al., 2006); therefore, in order to maintain structure and strength and to be as light as possible, as bone grows in some places it is removed from other places.

1.2 Assessing Maturation

In order to compare bone properties and strength in the growing skeleton it is important to know how biologically mature participants are. Because chronological age does not take into consideration any biological maturation markers (e.g. pubic hair growth, breast development, onset of menarche), it is challenging to compare data pertaining to growth simply by chronological age. Being able to align data using a common maturational landmark (e.g. age at peak height velocity, PHV) is important when participants of both sexes are experiencing growth at different rates. Interactions between sex and other potential determinants of bone properties and strength, such as physical activity, may be influenced by maturation (Valtuena et al., 2012; Chevalley et al., 2014). Using various methods, it is possible to define a participant's biological age (Tanner, 1975; Spampinato, 1995; Bailey, 1997). There are a couple methods that can be used to asses a participant's maturational age, like Tanner Stages (Tanner 1975) and the assessment of hand bones, but these methods are either ineffective due to self reporting or invasive (Tanner, 1975; Kirmani et al., 2009; Spampinato, 1995). In 1997, in combination with the Saskatchewan Pediatric Bone Mineral Accrual Study (PBMAS), Mirwald et al. (1997) developed a biological maturation tool that is efficient, non-invasive, and takes into account the sex-differences in growth. By calculating a participant's age from PHV (the age at which a participant experiences the fastest rate of growth) it is possible estimate their biological age, thereby enabling researchers, for example, to compare growth data between sexes (Mirwald et al., 2002). At present, age at PHV is regarded as a reliable indicator of maturity in both sexes and is commonly used to assess maturational age (Kirmani et al., 2009).

1.3 Wolff's Law and the Mechanostat Model

Wolff's Law, the forefather of the mechanostat model, conceptualized that "every change in the form and function of bone or of their function alone is followed by certain definite changes in their internal architecture and equally definite alteration in their external conformation, in accordance with mathematical law" (Wolff, 1892). This translation of the concept behind Wolff's Law was further explained by Frost (1998) saying that mechanical influences can affect bone. "Their bones, joints, ligaments, tendons, and fascia adapt to their voluntary mechanical usage in ways to keep them from breaking or hurting for life" (Frost 1998). The mechanostat model tries to explain bone adaptation to loading in terms of how bone mass is regulated by strain magnitude (Fig 1). For example, if bone experiences an external load, it will adapt bone mass (and structure) which will move the strain back into the acceptable (optimal) range (Frost, 1987). In order to reduce stress (force/unit area), if force remains constant, the cross sectional area (diameter) of the bone would have to increase. Thus, strain placed on a bone will stimulate the tissue, and the amount of modeling (growth) or remodeling (repair) that takes place will be dependent on the magnitude of the strain (Forwood & Turner, 1955). If the strain on the bone does not reach the normal level, the mechanostat works in reverse, lessening the amount of bone (or altering bone structure) as to keep up with the need for the lightest bone possible. Muscle, in relation to the mechanostat, is a key driving factor when it comes to bone modeling and remodeling as muscle contractions place the largest physiological strain on bone (Bonewald & Johnson, 2008; Földhazy, 2007).

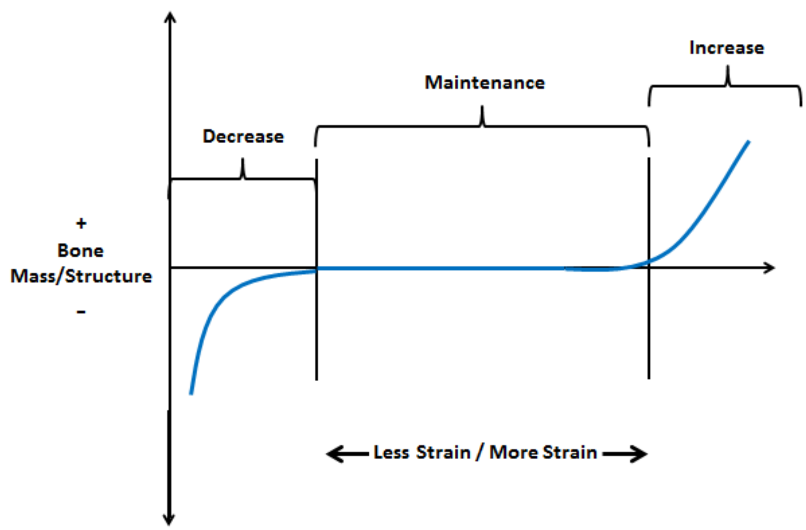


Figure 1: Mechanostat Model. The mechanostat model, adapted from Forwood and Turner (1995).

1.4 Muscle Bone Interaction

Muscle forces have a positive effect on bone (Rauch et al. 2004) and act on bone during all movements. The largest force by muscle acting on bone comes during locomotion and lifting activities (Rauch et al., 2004). The location of insertion of the muscle on the bone is typically close to the axis of rotation, and because of this the associated lever arm is small. A large amount of force has to be produced in order to overcome the effect of a small lever arm (Avin et al., 2015), and this force is transmitted through the skeleton (bone). For example, Avin et al, (2015) state that "the biceps brachii muscle has a lever arm that is approximately one tenth that of the center of mass of the forearm and, thus, the muscle needs to generate a force over 10 times the weight of the forearm in order to produce elbow flexion." Because of this mechanical disadvantage prevalent in the majority of the human body (Hamill & Knutzen), it has been suggested that forces exerted by muscle on bone are the leading source of mechanical loading that bone experiences (Avin et al., 2015).

The muscle-bone relationship that examines the effect of muscle forces on bone, characterized in children using peripheral quantitative computed tomography (pQCT) by Macdonald et al. (2006), was limited to calculated measures of force production rather than direct measures using a force plate. The muscle-bone relationship in growing children has not yet been characterized using HR-pQCT. This is important because, in order to develop activities that best promote bone strength during the peak opportunity for bone growth, we need to understand how specific muscle forces affect growing bone, both in terms of microstructure and strength.

1.5 Peripheral Quantitative Computed Tomography (pQCT) *in vivo*

Peripheral QCT is an imaging tool that can acquire scans of the appendicular skeleton and produce a cross sectional image of the scanned site. It allows researchers to evaluate the cross sectional geometry of the bone, as well as the size and density of the surrounding muscle and other tissue. pQCT provides values of total, trabecular and cortical cross-sectional area, bone mineral content (i.e. mass) and density at the distal site, and similar values at the shaft site of the radius and tibia. From these values, we can calculate bone strength indices of both the distal and shaft sites. Limited to the distal end of the radius and tibia, BSIc indicating the bones ability to withstand compressive forces (Pang & Lau, 2012), is a “compressive strength metric that combines volumetric bone density and geometry (i.e., total area) to estimate the compressive failure load of bone” (Crockett et al., 2015). BSIc is calculated by (total cross-sectional area) x (total bone mineral density)^2, and is assessed from a pQCT image of the distal site where compressive forces are most common (Kontulainen et al., 2008). Density-weighted polar section modulus strength–strain index (SSIp) at the shaft represents the bone’s ability to resist torsion (Kontulainen et al., 2008). SSIp refers to the distribution of mass about the central axis in the imaged cross-section of bone. Bone’s resistance to torsional loading increases with greater mass distributed further from the central axis. Like BSIc, SSIp is calculated using data about the geometric and densitometric properties of bone gathered from pQCT images at the shaft site.

Unlike dual energy x-ray absorptiometry (DXA) which takes a two dimensional (2D) areal measure of bone density (aBMD, mg/cm^{2}HA), the pQCT gives a three dimensional (volumetric) measurement of bone mineral density (vBMD, mg/cm^{3}HA). The pQCT produces images with voxels that typically measure 0.4×0.4×2.4 mm. Measuring bone structure at the shaft is less complicated than at the distal site because smaller bone structures, like trabeculae, are less prominent and cortical bone is thick. At the distal sites, pQCT can differentiate trabecular bone from cortical, but it cannot characterize thin bone structures like the cortical or trabecular thickness due to the limited voxel size. If the structure(s) being imaged (e.g. trabeculae) is smaller than that of the pixel size (0.4x0.4mm) (Burrows at al., 2010), it is not possible to produce an image that shows the structure clearly. In a study by Burrows et al. (2010), the average trabecular thickness found in boys (n=146) was 80µ and 72µ in girls (n=133). pQCT is not able to image these smaller bone structures; however, it is possible to use a high resolution pQCT to estimate these bone micro-architectural properties.

1.6 High Resolution Peripheral Computed Tomography

Cortet and Marchandise (2000) stated that bone microarchitecture-related factors may explain up to 30% of the variance in bone mechanical resistance (strength) beyond what is already explained by bone mass. This is important when considering how we are able to image bone microarchitecture in children. HR-pQCT, like conventional pQCT, is an imaging tool capable of capturing a highly detailed volumetric image of the appendicular skeleton (Fig 4). HR-pQCT has the smallest voxel size available for imaging humans at 82µ isotropic (*in vivo*) and can be set to a smaller size (41µ) for cadaveric (*ex vivo*) imaging. HR-pQCT is the first imaging modality that can measure bone micro-architecture in humans (XtremeCT User Manual). At 82µ, the HR-pQCT is capable of scanning some micro-architecture of trabeculae (Pagggiosi, Eastell & Walsh, 2013). Some of the trabeculae in children are smaller than the pixel size of the imaging machine. However, a study done by Krause et al (2013) showed that values measured from HR-pQCT compared with those of the gold-standard microCT correlated well. This indicates that we can rely on values derived by the HR-pQCT, even if the size of the micro-architectural features are less than that of the pixel size. Values from the HR-pQCT include total, cortical, and trabecular area, and density, cortical and trabecular thickness, trabecular number, and trabecular bone volume fraction. These measures, classified as bone microarchitecture, are important as they contribute to overall whole bone strength (Kawalilak et al., 2014). Unlike conventional pQCT, HR-pQCT is capable of rendering a three dimensional (3D) image of the bone. The conventional pQCT takes an image of only one slice over 2.4+/- 0.1mm, but the HR-pQCT takes a total of 110 slices over 9.02mm. Images from the HR-pQCT allow for differentiation between trabecular and cortical bone and estimation of trabecular number and thickness at the distal radius and tibia. Trabecular number and thickness are estimated through measuring the size and number of spaces between the trabeculae. The HR-pQCT cannot, however, take images of the midshaft of any extremity because the gantry of the scanner is not large enough to accommodate a full limb, thus the images produced by the HR-pQCT (Generation 1) scanners are used to measure the distal bone ends at the wrist and ankle.

Using a combination of conventional pQCT and HR-pQCT is one way to collect data that includes information of the cortical bone and muscle from the shaft site (pQCT) as well as micro-architecture information of the distal site (HR-pQCT). Having data from both sites allows us to view both the trabeculae and the bone micro-architecture in the ends of the bone, and the cortical bone in the shaft site, for a more comprehensive bone view.

1.7 Neuromuscular Performance

Muscle size (e.g. area) is commonly used as a surrogate measure to indicate neuromuscular performance; however, muscle size and the ability to use muscle are two different things. Rantalainen et al., (2010) stated that “neuromuscular performance should be measured and preferred over body mass in models predicting skeletal robusticity”. This means that it is important to include the participants’ muscular capacity, or their ability to produce force when looking at components of physical performance rather than just their muscle size. Bhatia et al. (2014) described bone strains deriving from physical activity as a “primary driver of bone adaptation” that cannot be measured in a non-invasive manner, and that physical activity may contribute to bone strength on a structural level, independent of bone mass or size (Bhatia et al., 2014). It is therefore important to find a way to non-invasively measure physical activity in relation to bone strength and structure. So, in addition to muscle size, neuromuscular performance can be measured using physical activities such as gripping, pushing or jumping.

1.7.1 Hand Grip

Hand grip strength, measured using a dynamometer, indicates force produced in kilograms. It is a consistent predictor of many physiological and health outcomes (Bohannon, 2008). It is also indicative of muscle mass, weight, height, and hand length in children (Häger-Ross and Rösblad, 2002). In a 2002 study by Häger-Ross and Rösblad, right handed children were stronger in their dominant hand by nearly 10% while left handed children did not differ significantly between limbs (Häger-Ross and Rösblad, 2002). Simple to use, relatively inexpensive, and portable (Bohannon, 2008), hand grip dynamometers give a good indication of forearm strength.

1.7.2 Push-ups

A push-up is a common activity that is inexpensive to perform because it requires very little, if any, equipment. Push-ups are a multi-joint upper-body exercise and can be included in an intervention or fitness program designed to improve bone health (Troy et al., 2013). Used in standardized fitness tests in schools, the push-up has been used to evaluate muscular strength and endurance (Lloyd et al., 2003; Mayhew et al., 1991). Push-ups yielded very similar results between sexes in children (Laughlin and Busk, 2007), and have many variations. Participants' muscular endurance, or time to voluntary exhaustion, is typically assessed by measuring the number of push-ups they are able to willingly do in a row. This repetitive movement is mechanically similar to children pushing on surfaces (e.g. doors) during daily movement. Explosive or maximal push-ups are where the participants try to propel themselves off of the ground while maintaining a proper push-up position. Measuring explosive maximal push-up force in children is not a common practice like the repetitive push-ups that measure muscular endurance; but, by measuring the maximal explosive force a participant can create, we can estimate the maximum force a participant's arms experience on a daily basis.

1.7.3 Jumps

Like doing push-ups in the forearm, jumping loads the bones of the lower body. Impact loading arising from a jump, versus normal weight bearing loading (standing), was significantly associated with bone architecture and strength in children (McKay et al., 2010). The standing long jump and the countermovement jump are both common tests used to measure the explosive leg strength in children (Huang & Malina, 2007; Castro-Pinero et al., 2010; Malina et al., 1995). Practically, the standing long jump (distance only), is better as a field test than the countermovement jump based on equipment needed; however, both jumps are cost/time efficient and require minimal equipment (Castro-Pinero et al., 2010). The standing long jump has been shown to be a good indicator of general muscular fitness in youth (Castro-Pinero et al., 2010). The countermovement jump has also been shown to be a good indicator of explosive muscular strength in the lower body (Castro-Pinero et al., 2010). Along with the standing long jump, it is used in many field based studies that looked at explosive muscular strength, (Huang & Malina, 2007; Castro-Pinero et al., 2010; Malina et al., 1995; Macdonald et al., 2007), and it is easy to administer. Estimated lower leg power has been measured in studies using a vertical jump height measurement and power calculation in children; however, countermovement jump force, impulse, and power have only been measured in premenopausal female athletes (Rantalainen et al., 2010). Conversely, the use of force plates would help to strengthen this measurement by measuring directly the ground reaction forces, thereby eliminating the need for a vertical height measurement. Both jumps rely on muscular strength, are easy to do and relatively time efficient for the number of measures that they provide.

1.7.4 Summary

The literature discussed the modeling and remodeling processes of bone. Altering its size and shape (modeling) to account for the load being placed on it while simultaneously repairing any small imperfections (remodeling), bone adaptation can be characterized by Wolf's Law and Frost's Mechanostat. The muscle-bone interaction is a paramount feature in the mechanostat principle (Frost, 1987). As the majority of the strain being placed on bone (especially in the upper limbs) is being caused by muscle forces (Rauch et al. 2004). Associating neuromuscular performance measures (hand grip, push-ups, and jumps) and with bone properties and strength is one way to estimate the effect muscle forces have on bone. Using a combination of pQCT and HR-pQCT imaging tools allows researchers to assess bone properties and strength both distally, at the ankle and wrist, and at the shaft site of the radius and tibia. The gap in the literature comes when examining the associations between neuromuscular performance and bone properties, including bone micro-architecture and strength in the growing skeleton. There is very little evidence linking loading of the lower limbs with bone micro-architecture and strength in children through the use of RCT's (Macdonald et al., 2007; Kontulainen et al. 2013; Farr, 2006; Nikander et al., 2010; Tan et al., 2014), and even less evidence pertaining to the fracture prone forearm.

2.0 STUDY OBJECTIVE / RESEARCH QUESTION / HYPOTHESES

The objective of this study was to assess the capability of neuromuscular performance to predict site-specific bone properties of the forearm (radius) and lower leg (tibia) in children.

Research question

Do neuromuscular performance measures independently predict variance in bone properties and strength in the 1) radius and 2) tibia when controlling for possible confounders of sex, maturation, body size, and physical activity?

Hypotheses

1. Muscle size, grip strength, peak maximal push-up force, or the number of push-ups will independently predict bone properties and strength in the radius (distal and shaft), after controlling for possible confounders of sex, maturation, body size, and physical activity.

2. Muscle size, peak forces, impulse, and power produced during countermovement or standing long jumps, or standing long jump distance will independently predict bone properties and strength in the tibia (distal and shaft), after controlling for possible confounders of sex, maturation, body size, and physical activity.

3.0 METHODOLOGY

3.1 Study design

This was a cross-sectional, observational study employing various imaging (pQCT, HR-pQCT) and physical assessment of children. With acquired data, we used exploratory analysis to build the most appropriate linear models to explain the statistical independent variance neuromuscular performance measures (grip strength, peak push-up force, number of standard push-ups, countermovement and standing long jump peak force, power, and impulse) predicted in bone properties (total, cortical, and trabecular content, area, and density, cortical and trabecular thickness, trabecular number, and trabecular bone volume fraction) and bone strength (polar stress-strain index and compressive bone strength index).

3.2 Participant Eligibility

All volunteering participants who met the inclusion criteria were measured. Participants were selected based on the eligibility criteria that they were between the ages of 8 and 14, were not taking any medication known to affect bone health (e.g. oral glucocorticoids), and had no known diseases or syndromes that affect bone growth patterns or bone health (e.g. Cerebral Palsy). Participants were excluded if they did not meet any of the inclusion criteria.

If a participant had any previous fracture history in their dominant limb, they were still eligible to participate in the study. Instead of having their dominant (previously fractured) limb imaged their non-dominant (non-fractured) limb was imaged, and all relating data points (grip strength, peak push-up force) used were directly related to the imaged limb.

3.3 Recruitment

The Saskatoon Public School Division (SPSD) was contacted to obtain permission to conduct research within the schools. Permission was granted for two schools. Both schools were interested in participating, and were sent information to be sent home with the children. We offered a short information session about the educational opportunities for the children to the volunteering school's teachers. In addition, a small presentation designed to fit within the school curriculum was offered to all teachers at the participating schools. This presentation was used in order to increase student awareness and promote participation in the study and included an interactive lesson on bone and muscle health.

Initially, detailed information packages were delivered to the schools to be disseminated to students in all grade 3-6 classes. The recruitment package contained a detailed description of the study, including information on what the study was about, why it is important, how it would be conducted, parental consent and child assent forms (Appendix A). After the first round of information packages were delivered to students, ~20 volunteers were recruited. A second strategy with a 1-page information letter to the parents (Appendix B) was then disseminated to the students, which saw a better response (~30 volunteers).

3.4 Measurement

3.4.1 Questionnaires

Two questionnaires were given to interested students approximately one week prior to their measurement date to take home and complete with the help of a parent/guardian.

Physical Activity Questionnaire for Children. The first questionnaire was a seven-day recall of the child's physical activity. The Physical Activity Questionnaire for Children (PAQ-C) (Appendix C) was used to subjectively measure self reported physical activity levels (Kowalski et al.). The PAQ-C included additional questions about the frequency and duration of specific sports, the perceived intensity of each activity and the type of activity (e.g. gymnastics, swimming, soccer) the child had participated in in the past 12 months. The information gathered from the PAQ-C details the amount of sport participation actively loading the forearm (e.g. gymnastics, wrestling) the child had. Specific information regarding forearm loading was important to consider when designing an intervention for future studies. It allowed us to determine if there was any specific sport, or activity, children with stronger bones participated in more frequently than those with less strong of bones.

Limb Dominance, Medical History and Health Questionnaire. The second questionnaire was a Limb Dominance, Medical History and Health Questionnaire (Appendix D). The purpose of this questionnaire was to determine which limb was the dominant one to be used for imaging, and whether the participant met the inclusion criteria. The questionnaire also included questions pertaining to ethnicity, previous fracture history, medication use, and menarche status of female participants in order to describe the participant characteristics.

The questionnaires were collected at the time of measurement at the College of Kinesiology. If a questionnaire was missing, or returned incomplete, participants were asked to complete the questionnaire with the Research Assistant before the testing session. If a participant was unsure of any answers, parents were contacted (via information provided in consent form) to ascertain any missing information.

3.4.2 Anthropometric Measures and Maturation

Participants' height and sitting height were measured using a wall stadiometer (Holtian Limited, Crymych, UK) to the nearest 0.1cm. The box used for sitting height was the same for every participant. Each measurement was taken three times and the median value was recorded. The participant's mass was measured once using a digital scale (Toledo Scale Company, Ontario, Canada) to the nearest 0.5kg. Participants were wearing light clothes and were barefoot during all measurements. Hand and leg dominancy was recorded from the previously mentioned Limb Dominance questionnaire, and biological age/maturation (years from age at peak height velocity) was estimated using validated equations (eq. 1A & B) (Mirwald et al. 2002):

Eq.1A (Male)

$$\text{Maturity Offset} = -9.236 + (0.0002708 * \text{Leg Length} * \text{Sitting Height}) + (-0.001663 * \text{Age} * \text{Leg Length}) + (0.007216 * \text{Age} * \text{Sitting Height}) + \left(0.02292 * \frac{\text{Weight}}{\text{Height}} * 100\right)$$

Eq.1B (Female)

$$\text{Maturity Offset} = -9.376 + (0.0001882 * \text{Leg Length} * \text{Sitting Height}) + (0.0022 * \text{Age} * \text{Leg Length}) + (0.005841 * \text{Age} * \text{Sitting Height}) - (0.002658 * \text{age} * \text{weight}) + \left(0.07693 * \frac{\text{Weight}}{\text{Height}} * 100\right)$$

Where length and height measurements are in centimeters (cm), weight (mass) is measured in kilograms (kg), and age is measured in years (y). Maturity offset and age from peak height velocity are synonymous. The equations are sex specific, male **(A)** and female **(B).**

Length of the dominant forearm and lower leg were measured using a flexible measuring tape to the nearest millimeter. The ulna was measured from the distal tip of the styloid process to the proximal tip of the olecranon to determine the length of the forearm. A single trained technician located the distal tip of the ulna styloid process and marked it with washable ink. Seated participants were then instructed to place their elbow, bent at 90°, on a flat surface (table top) and a measurement was taken from the drawn mark to the table top (olecranon). The ulna was used due to the easier nature of measurement when compared with the radius. To determine the length of the lower leg, the tibia was measured from the distal tip of the malleolus to the proximal edge of the tibial plateau. To measure the length of the tibia, seated participants were asked to cross their dominant ankle over their non-dominant knee, thus having the dominant tibia roughly parallel to the ground. The technician then located the distal end of the malleolus and the proximal end of the tibial plateau and placed marks accordingly. Measurements were taken three times per limb and the median was recorded and used for imaging.

3.4.3 pQCT Imaging

A single trained technician collected all pQCT scans from all participants. Following standard operating procedures for pQCT imaging the technician ensured that the participant was positioned correctly and comfortably in the machine before starting the scan. A scout view scan was used to determine the location of the end of the radius or tibia, and a reference line was placed accordingly (Fig 2). After the correct placement of the reference line, the image acquisition was started. The machine determined the location of the 4% and 65% of the radius and the 4% and the 66% site of the tibia using the measured length of the respective bone and took images at those specified locations. If a scan was determined to be unusable (e.g. the cortex of the bone was not continuous on the image), a rescan was done with the permission of the participant. If it was unlikely that a rescan was going to result in a more usable image (due to the participant's inability or unwillingness to sit still) no repeat scan was done. It was left to the discretion of the technician to determine if a repeat scan was necessary, or if it would result in a better image than the original.

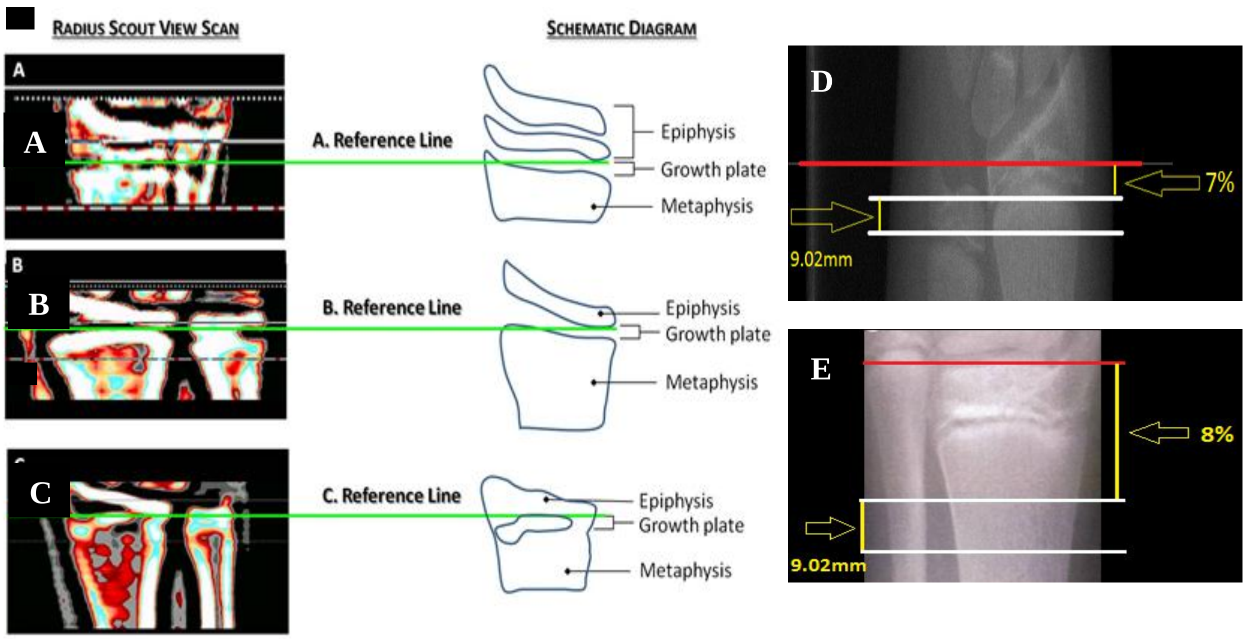


Figure 2: Scout View Scans. Radius scout view scans and correct reference line placement for pQCT **(A-C)**. Radius scout view scan and correct reference line placement (red line) for HR-pQCT **(D)**. Tibia scout view scan and correct reference line (red line) placement for HR-pQCT **(E).**

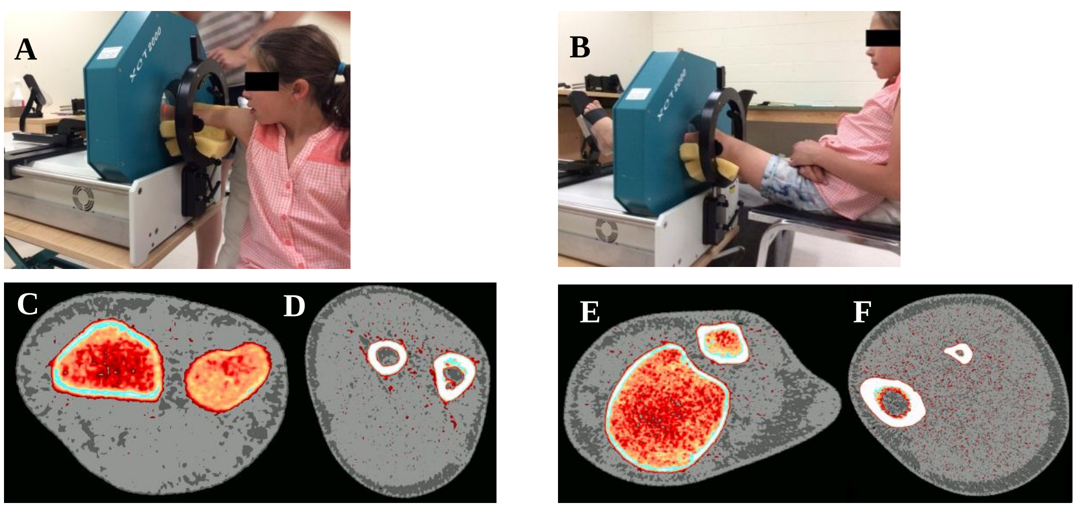


Figure 3: pQCT Machine and Images. Participant having pQCT scanning of her forearm **(A)** and tibia **(B).** Forearm scans are typically taken of the distal 4% site **(C)** and midshaft 65% site **(D).** Tibia scans are typically taken at the distal 4% site **(E)** and 66% site **(F).**

3.4.4 HR-pQCT Imaging

A single trained technician performed all HR-pQCT scans. Participants were placed comfortably into the imaging machine before scanning took place. A scout view scan was used to determine the correct position of the reference line and participants had their dominant forearm and lower leg scanned at the 7% and 8% sites (respectively) using HR-pQCT (HR pQCT, Xtreme CT; Scanco Medical, Switzerland). The imaging sites were determined using the UBC analysis protocol (Burrows et al., 2010; Liu et al., 2010). In the forearm, the reference line was placed at the most medial point of the distal radius, as shown in Fig 2D. For the lower leg, the reference line was placed at the most distal point of the tibial plafond. Each scan took approximately 2.5 minutes and was repeated if required with the permission of the participant and at the discretion of the technician. In order to determine if a repeat scan was needed, the technician viewed the first and last slices of the image. If there was significant movement in the image, the technician felt a repeat scan would be successful, and the participant agreed, a scan was repeated. Bone micro-architecture and volumetric densities at the distal forearm and tibia were measured.

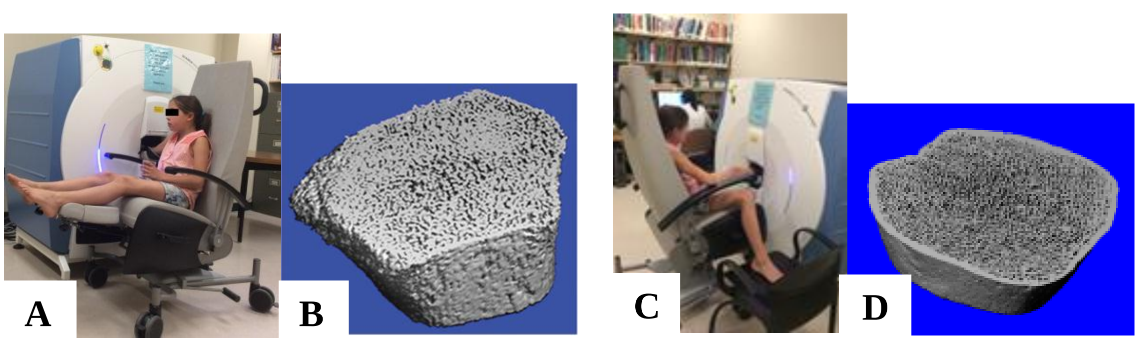


Figure 4: HR-pQCT Machine and Images. Participant having HR-pQCT scanning of her forearm **(A)** and tibia **(C).** Forearm scans are typically taken of the distal 7% site **(B)**. Tibia scans are typically taken at the distal 8% site **(D).**

3.4.5 Effective Radiation Dose

All participants were imaged by both pQCT and HR-pQCT. The total amount of radiation any participant was exposed to averaged less than 10μSv, but if a scan was needed to be repeated due to movement artifact, the maximum dosage of radiation was 12μSv as only one extra scan per limb was performed. This dosage of 12μSv includes scans from both imaging machines and is equivalent to the amount of background radiation a person would experience in two weeks in Saskatchewan (Health Canada, 2015).

3.4.6 Neuromuscular performance

In order to measure the participant's neuromuscular performance, they were asked to perform seven functional tests. These tests were performed in the Biomechanics of Balance and Movement Lab in the University of Saskatchewan, College of Kinesiology. Ground reaction force data from the hands (push-ups) and the feet (jumps) were collected using two force platforms (OR6-7, AMTI Watertown, MA) embedded into the lab floor. An 8-camera commercial motion capture system (Vicon Nexus, Vicon Motion Systems, CO) was used to collected 3D kinematics during push-ups. Before the testing procedure took place, a single reflective sphere (~14mm diameter) was placed, using double sided hypoallergenic tape, at the top of the participants back, centered between their shoulder blades in order to track the vertical movement of the upper body during the push-up movements. The reflective sphere allowed the motion capture system to collect data on the 3D location of the participant and help to identify specific phases in movement. Force data were sampled at 2000 Hz while kinematic data were synchronously sampled at 100 Hz. The data collected from the tracking of the sphere in addition to force data collected were combined using Matlab (R2006b) to calculate additional variables such as mechanical power and impulse.

Hand Grip Strength. Using a hand grip dynamometer (ORTHOCANADA, QC), participants were asked to squeeze as hard as they could with both their dominant and non-dominant hands, individually, three times. The participant was instructed to maintain a 90˚ elbow angle and to ensure their elbow and forearm did not make contact with the rest of their body (Fig 5). The participants alternated between hands in order to ensure fatigue was not a factor. All three trials were recorded and the median measurement was used for statistical analysis.

Figure 5: **Hand Grip Test Positioning.** A participant demonstrating the use of a hand grip dynamometer

Maximal Push-Up. Participants were given a demonstration and then asked to perform a single maximal push-up as best they could. Two hand positions were used during the test. The narrow hand position had the participant with their hands beneath their shoulders, thumbs roughly by the armpit when in the down position. The wide hand position had the participant with their hands outside of their shoulders, thumbs just touching their shoulders when in the down position. Participants performed a single maximal push-up from the “up” position, arms extended in front of the body, back, hips and legs straight, they lowered themselves to the “down” position, straight body, elbows bent to at least 90˚, while maintaining a straight line along their back and legs from the shoulders through the hips to the ankles. They exploded upward, propelling themselves past the initial “up” starting position. The participants were encouraged to propel themselves off of the floor as hard and fast as they could. They were told that clearing the ground was not necessary if they could not do the movement safely. When a participant was ready to start a push-up, they were in the up position, and the lab technician said “go-ahead.” When the participant had reached the “down” position, the lab technician said “push!” to indicate to the participant that they should start pushing as hard as they could. The push-ups were done with each hand placed on individual force plates. The starting form (hands on the floor, arms extended in front of the body with a straight line from shoulders to hips to ankles) of all push-ups (maximal push-ups and standard push-ups (listed below) was the same and can be seen in Fig 6. The single maximal push-up was performed three times and repeated a fourth time if any of the first three trials were poor. For the purpose of this study, a trial was deemed as poor if any of the following criteria were visually identified: 1) if the participant did not bend their arms past a 45˚ angle at the elbow, the push-up did not count; 2) the participant did not stop at the bottom (down position) of the push-up and let any part of their body (belly or knees) rest on the ground before completing the explosive phase of the push-up; 3) the participant used momentum created by kicking their feet in the air first to get their torso to move upward rather than using only their arms. If a participant made any one of these three major technique errors, a second demonstration was given, and the trial was repeated. The decision to repeat the trial was at the discretion of the technician, but was ultimately up to the participant. The maximum force recorded during the upward phase of the movement (verified by the motion capture data) from the dominant arm from all three trials was used for statistical analysis (Fig 7).

Figure 6: Push-up Starting Form. A participant demonstrating the starting position of the maximal and standard push-up tests

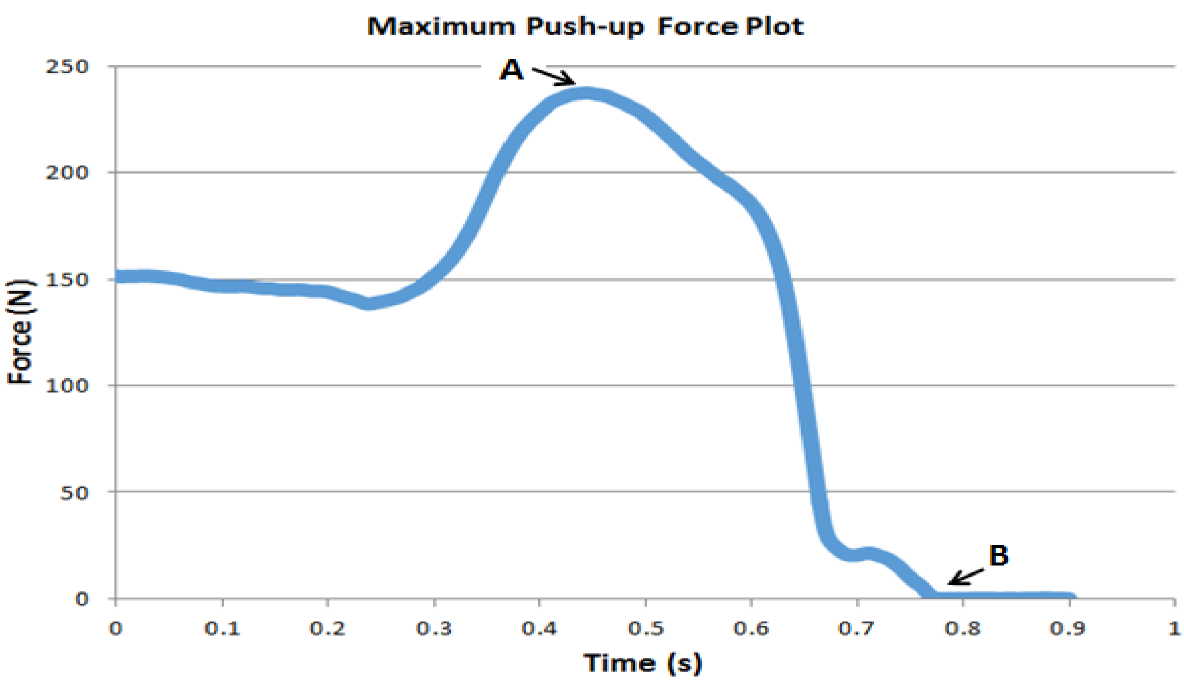


Figure 7: Maximum Push-up Force Plot. This figure shows the force curve of a maximum push-up. Point **(A)** shows the location of the peak force of the explosive phase of the push-up. Point **(B)** shows the point at which the participants hands left the force plate. Peak force was identified as the highest point on the curve during the explosive (eccentric) phase of the push-up, and was located using custom software (Matlab R2006b).

Number of Standard Push-Ups. A demonstration was given to the participants and they were asked to perform as many standard push-ups as they could in a row. Their hands were placed on individual force plates (one hand per plate) as they were during the maximal push-up test, using both narrow and wide hand positions. The starting position, or "up" position, has the participant with their hands placed comfortably beneath their shoulders on the force plates, their back and stomach in a neutral position, their legs straight, and their toes on the floor. Participants were instructed to lower their body to the "down" position, with their elbow bent to a 90˚ angle, before returning to the "up" position. One push-up was counted when a participant had moved from the "up" position, through the "down" position, and returned fully to the "up" position. Only consecutive push-ups were counted. The test ended when a participant could no longer maintain a proper body position for more than two push-ups in a row, or when they could no longer continue. This format followed the protocol from a school based test called FITNESSGRAM (Eather et al. BMC Public Health 2011).

Maximal Knee Push-Up. The maximal knee push-up test was identical to that of the maximal standard push-up test except that the participants were instructed to have their knees on the ground in addition to their feet, decreasing the length of the moment arm created by their body, and lessening the force required to explode off of the ground. Again, two different hand positions were used for this test. Data from this test was only used if participants could not perform a single push-up (N=2).

Number of Knee Push-Ups. The number of knee push-ups a participant could perform was demonstrated, performed, and recorded with the same protocol as the standard push-up test. Again, this test was only offered as an option if the participant could not perform a single standard push-up (N=2).

Countermovement Jump. Participants were given a demonstration of a countermovement jump, and then asked to perform three successful single jumps. The demonstration included verbal cues and movement at the same time. While standing in the middle of the force plate, the technician told the participants that their feet should be comfortably apart, and that they needed to do a smooth movement. While performing a jump, the technician said (and followed the cues) “hands in the air, squat bringing your hands down, and jump as high as you can, trying to touch the ceiling.” Participants were then asked if they have any questions, and to show the technician what they thought the jump should look like. If the technician was satisfied that the participant had understood, (i.e. they performed the jump as demonstrated and described to them) the participant was allowed to continue with testing. If the participant was not successful in performing the desired jump, another demonstration was given with verbal cues such as “very good, but don’t stop at the bottom” to remedy the error in the participants jump. A countermovement jump was started from the middle of a single force plate (Fig 7A), and consisted of a squatting motion followed by an explosive upward propulsion, which did not restrict hand or arm movement. The jump was expected to be smooth and the participant was not to stop at the bottom of the movement. A jump was considered successful when a participant was able to squat and take off in one smooth motion without stopping at the bottom. It was not necessary for participants to land back onto the force plate. Force-time data were recorded during the push off phase and peak force was obtained. Net impulse was calculated by using numerical integration to find the area under the force-time profile while taking gravity into account. Mechanical power was estimated by converting the force-time curve into vertical acceleration (by dividing the force by the mass and accounting for gravity) and integrating the resulting acceleration curve to obtain the vertical velocity profile (assuming an initial vertical velocity of 0 m/s). The vertical velocity data were then multiplied by the vertical force data to obtain the mechanical power profile and maximum power was calculated. All calculations were performed using custom software (Matlab R2006b) (Fig 8).

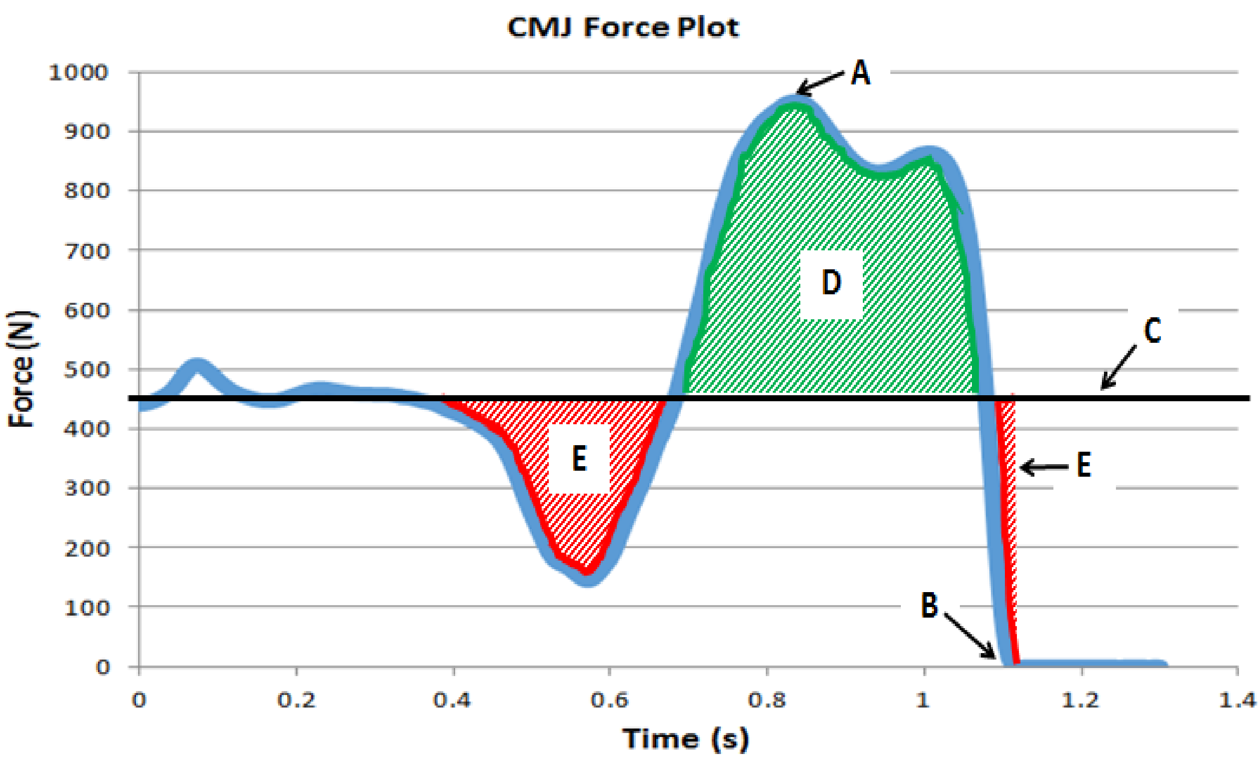


Figure 8: Countermovement Jump Force Plot. This figure shows the force curve of a countermovement jump. Point **(A)** shows the location of the peak force of the explosive phase of the jump, and was defined as the highest point on the curve during the jump before the participant left the ground at point **(B)**. The line at point **(C)** shows body weight (gravity). Section **(D)** defines the positive area under the curve. Sections **(E)** define the negative area under the curve. Net impulse was calculated by using numerical integration to find the area under the force-time profile **(D & E)** while taking gravity **(C)** into account. Mechanical power was estimated by converting the force-time curve into vertical acceleration (by dividing the force by the mass and accounting for gravity) and integrating the resulting acceleration curve to obtain the vertical velocity profile (assuming an initial vertical velocity of 0 m/s). The vertical velocity data were then multiplied by the vertical force data to obtain the mechanical power profile and maximum power was calculated. All calculations were performed using custom software (Matlab R2006b).

Standing Long Jump. A demonstration of the standing long jump was given to the participants before they were asked to complete three single jumps. The standing long jump was performed by the participants jumping from both feet centered on a single force plate, and landing with both feet on a mat placed on the ground for safety (Fig. 9A-C). The distance from the front of the participant's toes before takeoff (start line) to the back of the participant's heels upon landing was measured and recorded. The protocol used for the standing long jump was the EUROFIT protocol for children (Sauka et al. Scandinavian Journal of Public Health; Oja and Jurimae Percept Mot Skills 2002). The verbal cues during the demonstration included where to have your toes before the jump, jumping with both feet at the same time, landing with both feet as best as possible, and staying where you land so your jump distance can be measured. The force plate measured the ground reaction forces and provided values for vertical and horizontal peak force. Mechanical power and impulse were calculated using the same procedures as described in the previous section. Mean distance jumped was also recorded.

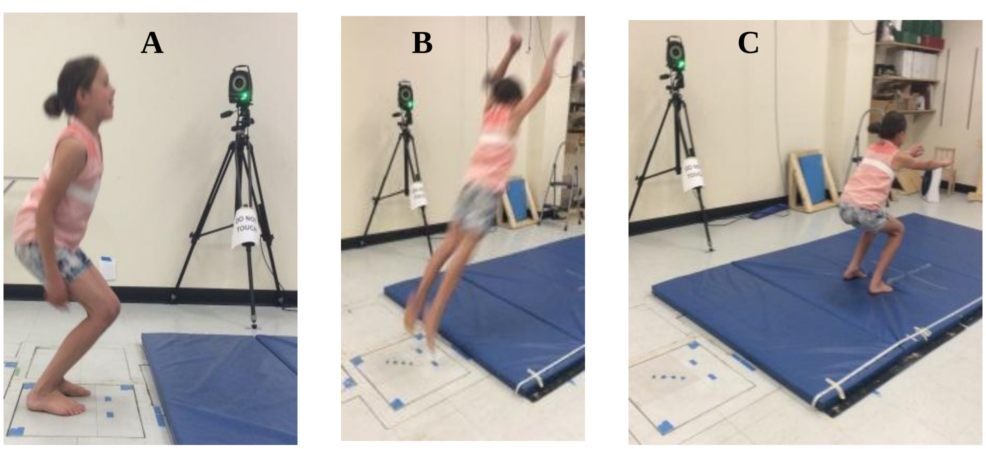


Figure 9: Phases of a Jump. The same starting position was used for both the countermovement and long jumps. A participant during the start of a jump **(A)**, during take-off **(B)**, and landing **(C).**

It is important to note that each of the upper limb tests were interspersed with the lower limb tests in order to reduce the effect of fatigue. The order the tests for all participants were performed as follows:

1. Hand Grip
2. Reflective Marker Placement
3. Maximal Push-up (Narrow)
4. Standing Long Jump
5. Number of Push-ups (Narrow)
6. Countermovement Jump
7. Maximal Push-up (Wide)
8. Break (1-2 minutes)
9. Number of Push-ups (Wide)

If a participant could not perform a single push-up (a total of two participants were unable to do so), the knee push-up protocol was used in place of the normal push-ups during all push-up tests.

3.5 Variable Summary

Neuromuscular performance measures were matched to appropriate bone outcome measures based on the expected relationship to the specific anatomical sites (Table 1).

Table 1: Variable Summary. A site specific summary of variables used in this study.

Site	Neuromuscular Performance Measures	Bone Outcomes	
Distal Radius	Muscle Area	Total Area	Cortical Thickness
	Grip Strength	Cortical Area	Trabecular Thickness
	Maximal Push-up Peak Force	Trabecular Area	Trabecular Number
	# of Standard Push-ups	Total Density	Trabecular Bone Volume Fraction
	Physical Activity	Cortical Density	
		Trabecular Density	BSIc
Radius Shaft	Muscle Area	Total Area	SSIp
	Grip Strength	Cortical Area	
	Maximal Push-up Peak Force	Cortical Density	
	# of Standard Push-ups	Total Content	
	Physical Activity Score	Cortical Content	
Distal Tibia	Countermovement Peak Force	Total Area	Cortical Thickness
	Countermovement Impulse	Cortical Area	Trabecular Thickness
	Countermovement Peak Power	Trabecular Area	Trabecular Number
	Long Jump Peak Vertical Force	Total Density	Trabecular Bone Volume Fraction
	Long Jump Peak Horizontal Force	Cortical Density	
	Long Jump Vertical Impulse	Trabecular Density	BSIc
	Long Jump Horizontal Impulse		
	Long Jump Peak Vertical Power		
	Long Jump Peak Horizontal Power		
	Physical Activity Score		
Tibia Shaft	Countermovement Peak Force	Total Area	SSIp
	Countermovement Impulse	Cortical Area	
	Countermovement Peak Power	Cortical Density	
	Long Jump Peak Vertical Force	Total Content	
	Long Jump Peak Horizontal Force	Cortical Content	
	Long Jump Vertical Impulse		
	Long Jump Horizontal Impulse		
	Long Jump Peak Vertical Power		
	Long Jump Peak Horizontal Power		
	Physical Activity Score		

3.6 Statistical analysis

3.6.1 Data Collection / Processing / Descriptive Statistics

A total of 380 students were invited to participate in the study. Of the invited participants, 81 of them agreed to participate. Three participants' data were removed before data analysis. Two of the participants (1 boy, 1 girl) were non-compliant, and data was rendered unusable. This was because they were only able to perform one of the seven neuromuscular performance tests (hand grip), and did not follow the instructions for the rest of the tests. Also, all six of their scans (4 pQCT, 2 HR-pQCT) had significant movement artifact and were unusable. One participant did not meet the eligibility criteria as she had Cerebral Palsy. In total, 79 participants (37 boys and 42 girls) met the study criteria and were included in the analysis. Descriptive statistics are shown below in Table 2 along with a flow chart of participant recruitment and data processing (Fig.10).

Table 2: Description of Participants. Descriptive statistics (mean ± SD) of participant characteristics.

Description of Participants

	Males N=37	Females N=42
Age (years)	10.5 ± 1.7	10.5 ± 1.6
Maturation (aPHV)	-2.6 ± 1.4	-1.4 ± 1.4
Height (cm)	143.8 ± 11.7	142.4 ±10.1
Sitting Height (cm)	75.1 ± 6.7	74.2 ±5.6
Weight (kg)	37.1 ± 10.9	35.8 ± 8.0
Ulna Length (mm)	229.7 ± 22.5	225.0 ± 18.3
Tibia Length (mm)	344.3 ± 32.4	339.3 ± 29.4

aPHV = Years from estimated PHV

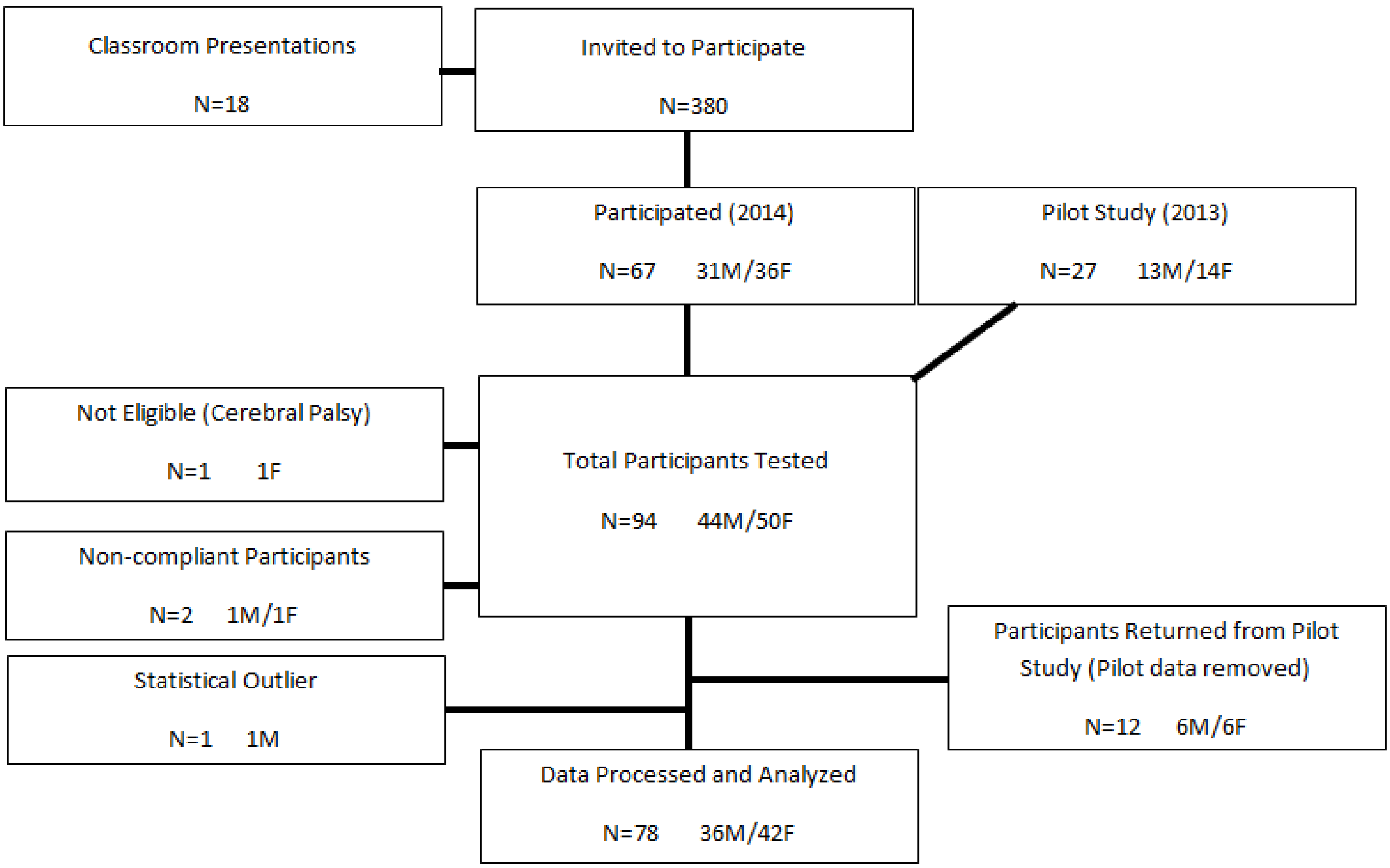


Figure 10: Recruitment and Analysis Flow Chart. A flow chart depicting participant recruitment and data analysis process

3.6.2 Checking for Normality

Normality of the data was checked using the Shapiro-Wilk's test in SPSS and outliers were defined as data values that were two standard deviations from the mean. A single participant, found to be more than three standard deviations above the mean in height, seated height, weight, ulna and tibia length, was classified as an outlier and removed from the data set. Once the outlier, described in Table 3, was removed all but six of the bone outcomes (cortical area and trabecular and cortical thickness at the distal radius, cortical thickness at the distal tibia, and SSIp and total density at the tibia shaft) met the assumption of normality for parametric analysis. As this data was being used in the form of exploratory analysis, the rest of the data was not transformed. A summary of the Shapiro-Wilk's test both before and after removing the outlier can be found in Appendix E.

Description of Outlier	
Sex	Male
Age (years)	14.1
Maturation (aPHV)	+1.4
Height (cm)	186.4
Sitting Height (cm)	96.1
Weight (kg)	84
Ulna Length (mm)	307
Tibia Length (mm)	465

Table 3: Description of Outlier. This table represents the descriptive statistics of the single outlier. Identified outliers, defined as falling outside two standard deviations from the mean, were removed from the data set.

3.6.3 Building Linear Regression Models

Using the Statistical Package for Social Sciences (SPSS, v. 16.0 for Windows; SPSS Inc., Chicago, IL, USA), with a level of significance set at a $p \leq 0.05$, forced entry linear regressions were used to explore the predictive ability of neuromuscular performance measures on bone properties and strength outcomes after controlling for possible confounders of sex, maturation, age, and body size at the radius and tibia. To build the regression models, possible predictors were examined in order to decide their importance. By running a set of bivariate correlations the most appropriate set of predictors for the base model was determined. Those predictors included sex, maturational age, weight, and limb length. Since sex was highly correlated with over half of the bone parameters analyzed in the tibia, it was forced into the model to account for sex differences. Weight was included as a measure of body size. Limb length, as opposed to height, was more highly correlated to the bone parameters in both the arm and the leg and also takes into account the direction of growth. As children typically grow from the hands and feet inward (Mirwald et al., 2002), using limb length may also help to further align participants by maturation.

Once the confounding factors were selected, two step forced entry linear regression models were created. Limb specific models consisted of a forced base model (sex, maturation, weight, and limb length), followed by individual neuromuscular performance measures and individual bone parameters. After adjusting for sex, maturation, limb length and weight, neuromuscular performance measures were included in the regression model individually in order to find the amount of variance in each individual bone property predicted by a single neuromuscular performance measure. Independent predictors were entered into the models individually due to the exploratory nature of this study and the small number of participants. We report descriptive statistics, adjusted R^2, change in R^2, and partial r and R^2 values to assess the ability of the created models and independent variables to predict bone outcomes. Examples of the linear regression models for each limb can be found below in Table 4. See Appendix F for the full set of regression models.

Table 4: Example Regression Models for Radius. An example of regression models created for the distal radius predicting the variance in total bone area. Each model consists of the base model and the single independent neuromuscular performance measure being assessed. Bold values represent models that were significant p≤0.05.

Distal Radius: Total Area

	Independent Variables	Overall R2	R2 Change	partial r	Partial R2	Beta	p-value
Base		0.312					
	Sex			0.328	0.108	0.278	0.023
	Maturation			0.236	0.056	0.313	0.107
	Weight			0.120	0.014	0.201	0.417
	Limb Length			0.036	0.001	0.067	0.810
Model 1		**0.425**	**0.115**				
	Sex			**0.204**	**0.042**	**0.160**	**0.169**
	Maturation			**0.275**	**0.076**	**0.333**	**0.062**
	Weight			**-0.190**	**0.036**	**-0.375**	**0.201**
	Limb Length			**0.093**	**0.009**	**0.159**	**0.535**
	Muscle Area			**0.427**	**0.182**	**0.605**	**0.003**
Model 2		0.345	0.008				
	Sex			0.338	0.114	0.287	0.022
	Maturation			0.232	0.054	0.292	0.121
	Weight			0.089	0.008	0.143	0.555
	Limb Length			0.075	0.006	0.138	0.618
	Physical Activity Score			0.118	0.014	0.094	0.434
Model 3		**0.453**	**0.114**				
	Sex			**0.367**	**0.135**	**0.282**	**0.008**
	Maturation			**0.090**	**0.008**	**0.103**	**0.554**
	Weight			**-0.071**	**0.005**	**-0.116**	**0.620**
	Limb Length			**0.114**	**0.013**	**0.194**	**0.426**
	Grip Strength (Mean)			**0.432**	**0.187**	**0.498**	**0.002**
Model 4		0.341	0.029				
	Sex			0.341	0.116	0.291	0.016
	Maturation			0.258	0.067	0.356	0.074
	Weight			0.194	0.038	0.372	0.182
	Limb Length			0.011	0.000	0.020	0.941
	Max Push-up Peak Force			-0.216	0.047	-0.256	0.136
Model 5		0.331	0.007				
	Sex			0.259	0.067	0.232	0.066
	Maturation			0.170	0.029	0.226	0.232
	Weight			0.091	0.008	0.154	0.524
	Limb Length			0.107	0.011	0.200	0.456
	Standard Push-Up Test #			0.108	0.012	0.093	0.450

4.0 RESULTS

4.1 pQCT Results

Results varied depending on the limb for both pQCT and HR pQCT bone outcomes. For each bone outcome and limb, sex, maturation, weight, and limb length were forced into the regression model first, followed by individual neuromuscular performance measures.

4.1.1 Forearm

At the radius shaft, up to 43% of the variance in total and cortical area, cortical density, and SSIp were predicted with models including muscle area (9-22%) and grip strength (6-16%) as independent predictors (Fig 11). BSIc at the distal radius was predicted up to 23% by models with muscle area (15%) and physical activity score (7%) as independent predictors (Fig 12). All other bone parameter measured using pQCT at the radius shaft were insignificant (p>0.05). For a full set of regression tables see Appendix F.

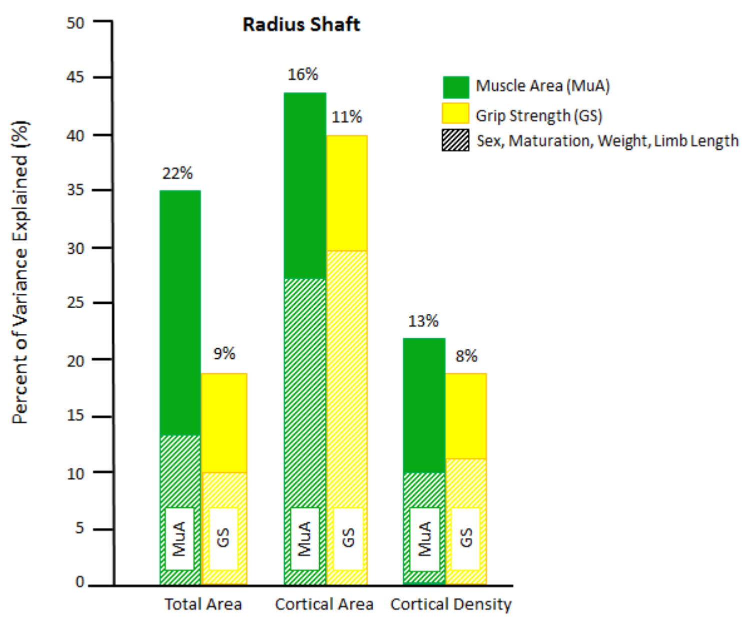


Figure 11: Percent of Variance Explained in Bone Outcomes at the Radius Shaft. Bars represent variance (%) in bone outcomes predicted by independent (p<0.05) muscular predictors and confounders (sex, maturation, weight, and limb length) at the radius shaft when measured using pQCT. % values listed above bars represent the independent variance predicted by the neuromuscular performance measure.

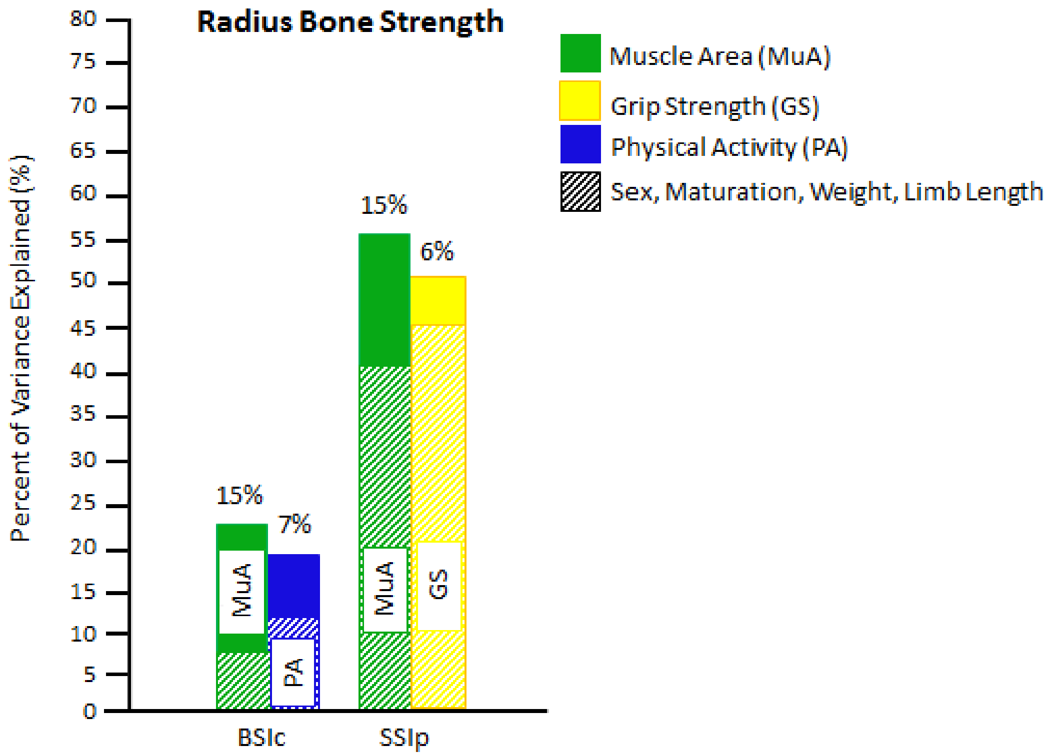


Figure 12: Percent of Variance Explained in Bone Strength at the Radius.
Bars represent variance (%) in bone strength predicted by independent (p<0.05) muscular predictors and confounders (sex, maturation, weight, and limb length) at the radius when measured using pQCT. % values listed above bars represent the independent variance predicted by the neuromuscular performance measure.

4.1.2 Lower Leg

At the tibia shaft, up to 62% of total area was predicted by models using muscle area (28%), countermovement jump impulse (8%), and standing long jump horizontal impulse (8%) as independent predictors. 72% of cortical area was predicted by the model with countermovement jump maximum force (6%) as the independent predictor. Up to 78% of total and cortical content were predicted by models using countermovement maximum force (9%), standing long jump vertical force (6% and 10%, respectively), and standing long jump peak vertical power (8% and 6%, respectively) as independent predictors. Cortical content was also predicted by standing long jump horizontal force (6%). Up to

37% of cortical density was predicted by models with muscle area (24%), standing long jump maximum horizontal force (6%), standing long jump vertical (8%) and horizontal impulse (7%), and standing long jump peak horizontal power (5%) as independent predictors. 78% of SSIp was predicted by the model that used muscle area (5%) as the independent predictor (Fig 14). 36% of BSIc at the distal tibia was predicted by the model using standing long jump peak vertical power (8%) as the independent predictor (Fig 14). All other bone parameters measured using the pQCT at the tibia shaft were insignificant. For a full set of regression tables see Appendix F.

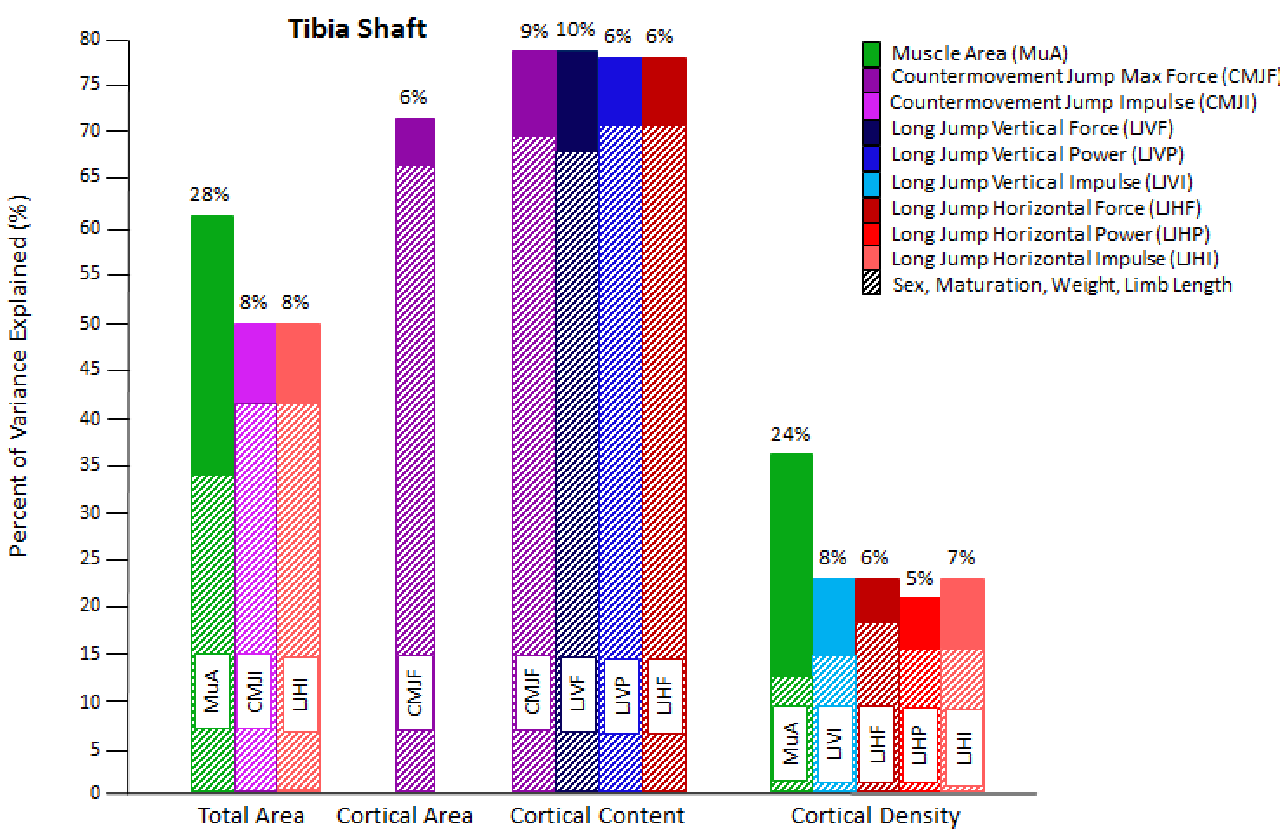


Figure 13: Percent of Variance Explained in Bone Outcomes at the Tibia Shaft. Bars represent variance (%) in bone outcomes predicted by independent (p<0.05) muscular predictors and confounders (sex, maturation, weight, and limb length) at the tibia shaft when measured using pQCT. % values listed above bars represent the independent variance predicted by the neuromuscular performance measure.

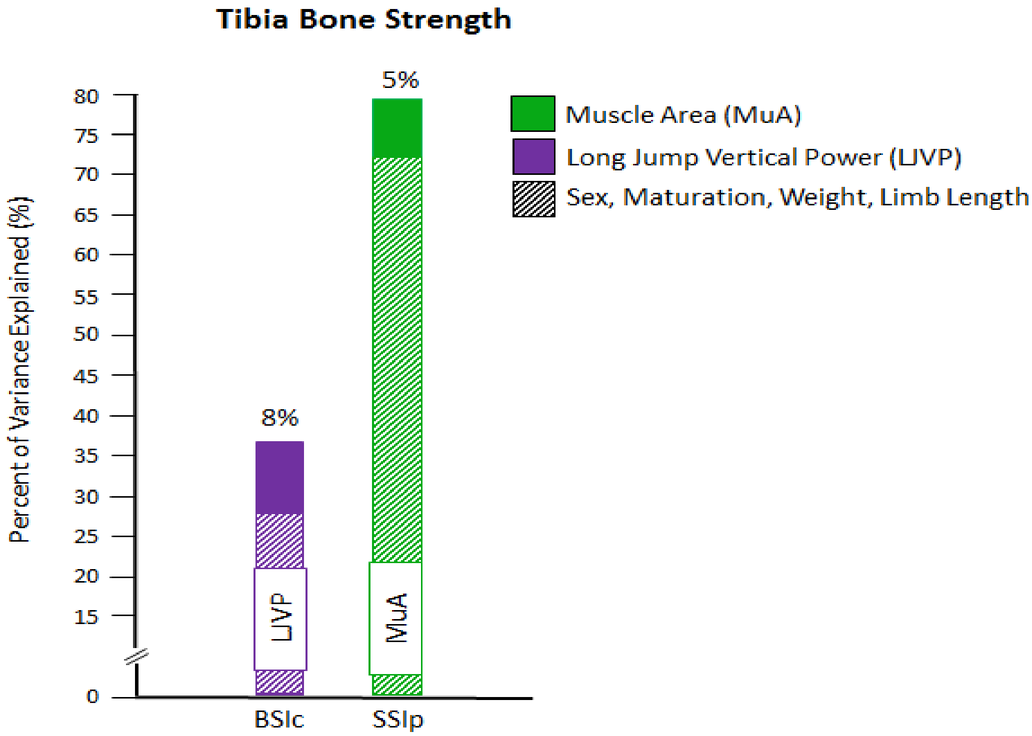
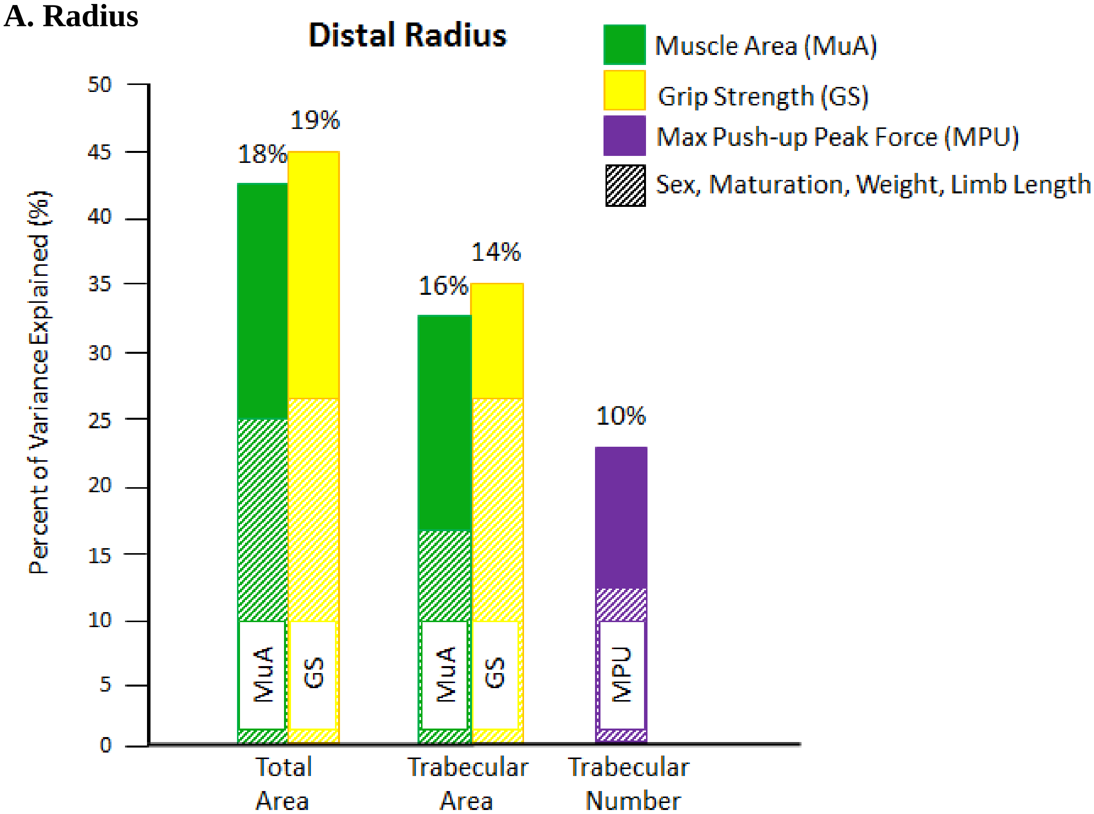


Figure 14: Percent of Variance Explained in Bone Strength at the Tibia (B).
Bars represent variance (%) in bone strength predicted by independent (p<0.05) muscular predictors and confounders (sex, maturation, weight, and limb length) at the tibia when measured using pQCT. % values listed above bars represent the independent variance predicted by the neuromuscular performance measure.

4.2 HR-pQCT Results

At the distal radius, up to 45% of the variance in total and trabecular area were predicted with models including muscle area (18% and 16%, respectively) and grip strength (19% and 14%, respectively) as independent predictors. The model with peak push-up force (10%) predicted 23% of the variance in trabecular number (Fig 15A). At the tibia, the model with physical activity (9%) predicted 24% of the variance in trabecular number (Fig 15B).

A. Radius



B. Tibia

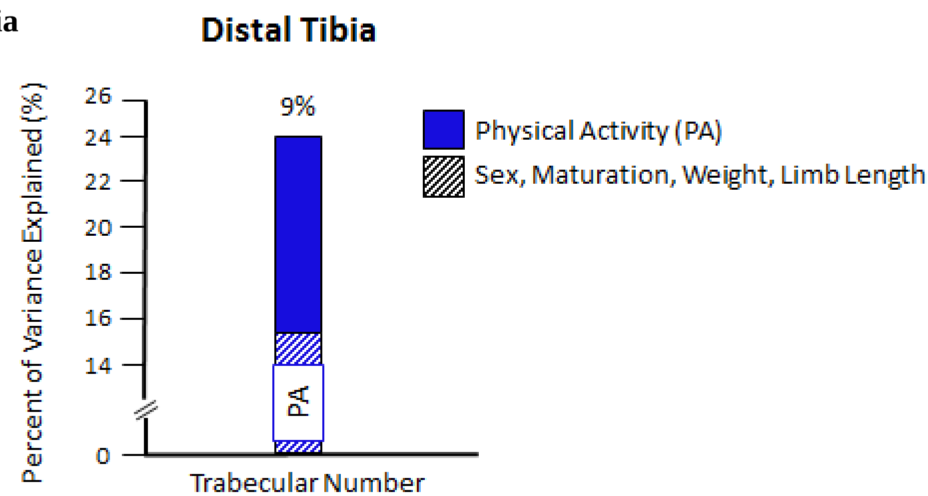


Figure 15: Percent of Variance Explained in Bone Outcomes at the Distal Radius (A) and Tibia (B). Bars represent variance (%) in bone outcomes predicted by independent (*p*<0.05) muscular predictors and confounders (sex, maturation, weight, and limb length) at the distal radius and tibia when measured using HR-pQCT. % values listed above bars represent the independent variance predicted by the neuromuscular performance measure.

5.0 DISCUSSION AND CONCLUSION

5.1 Discussion

The objective of this study was to assess the capability of neuromuscular performance measures to predict bone properties in the forearm (radius) and lower leg (tibia) in children.

The first hypothesis, which tested the predictive ability of neuromuscular performance on bone parameters and strength at the forearm, was only partly supported. Muscle area and grip strength independently predicted both total and trabecular area. While not predicting as many bone parameters as expected, these two measures of muscle size and neuromuscular performance appeared similar to other samples studying similar populations (de Smet & Vercammen, 2001). Muscle area and grip strength independently predicted between 6% - 22% of the variance in bone parameters at the radius shaft and between 9% and 19% of the variance in bone parameters at the distal radius. These outcomes included total and cortical area, cortical density, and SSIp at the shaft site and total and trabecular area, trabecular number, and BSIc at the distal site. This suggests that targeted exercises designed for increasing forearm muscle size and grip strength may be beneficial in an intervention designed to improve bone strength in the forearm in children.

Muscle area and physical activity score independently predicted BSIc at the distal radius. In previous literature, it has been shown that muscle area has been the “primary explanatory variable” in bone strength at the distal tibia in children, and that physical activity corresponded with an increase in BSIc (Macdonald et al., 2006). Our results indicate that physical activity is also an explanatory variable of BSIc. Although Macdonald et al's (2006) UBC study did not use the PAQ-C used in this study, they did use a similar questionnaire to measure a physical activity score. Our participants mean physical activity score (3.32/5) was above that of the UBC study (2.7/5), for both boys and girls. This might be due to the geographical location difference of large city (population>2million) versus a more rural mid-sized city (population~200,000) as it has been shown that rural children are more physically active and fit when compared alongside city dwelling children (Salmon et al., 2013; Karkera et al., 2013).

In previous studies the focus on push-ups has been limited to endurance (the maximum number a participant can do) rather than explosive push-up force (Castro-Pinero et al., 2010; Lloyd et al., 2003; Mayhew et al., 1991). Our study found that an endurance style push-up measurement was not associated with bone outcomes whereas the maximum push-up force independently predicted variance in trabecular number in the distal radius. This result is not comparable to other studies because explosive push-ups have not been used as a measure of neuromuscular performance in children before now. However, these findings agree with experimental evidence from animal studies and observations from adult endurance athletes indicating that duration of loading stimulus is not important for bone adaptation to loading (Robling et al., 2002).

The second hypothesis, testing the predictive ability of neuromuscular performance measures (i.e. forces and distance during jumping) at the tibia, was only partly supported if each jumping component was examined individually. If, however, the components of a countermovement and standing long jump are combined and considered as a whole, the findings support this hypothesis. At least one component of both jumps independently predicted all bone parameters measured, except trabecular thickness and area. As the neuromuscular performance measures (force, impulse and power) from the countermovement jump have only been measured in premenopausal women athletes (Rantalainen et al., 2010), this study provides a novel piece of information to the literature. Specifically, this study shows that the variance in total area at the tibia shaft was independently predicted by countermovement jump impulse. Also, the variance in cortical area and total and cortical content were independently predicted by countermovement jump maximum force. Further research with a larger sample size is needed to confirm these observations. In the study by Rantalainen et al (2010) the countermovement jump performance measures (force, impulse, and power) independently predicted up to 9% of the variance in bone strength measures (BSIc and SSIp) while only standing long jump predicted the variance in this study. The discrepancy between the adult measures from Rantalainen et al, (2010) and this study might be due to the technique aspect of the measurement. For example, it was clear when watching children perform their first countermovement jump that further explanation and demonstration was needed. Verbal cues (down and up/jump) were given during the testing to try to limit the effect of technique. After the second countermovement jump, children were better at performance, but still lacked certain finesse when jumping that would allow for a wholly repeatable movement. There is currently no data exploring the precision of the countermovement jump in children in the literature. And, as previous studies only report standing long jump distance and not take off (vertical and horizontal) forces, power or impulse, this study adds to the literature pertaining to standing long jump measures in healthy children (Macdonald et al., 2007).

Muscle area significantly predicted 6 out of 13 bone parameters measured at the tibia ranging from 6% to 28% of the variance predicted by the independent predictors. The bone outcomes that were independently predicted included total and cortical area and content, cortical density and SSIp. BSIc was only independently predicted by standing long jump peak vertical power. These findings suggest that the ability to use the muscle rather than the size of the muscle is more important in predicting bone properties and strength in the tibia in children. This follows with findings of another study (Macdonald et al., 2007), and suggests that optimising force, power, and impulse in the lower legs may be an important focus when designing an intervention designed to improve bone strength in the tibia. In addition to using a “well supported and flexible active school model” like in Action Schools! BC (Macdonald et al., 2007), strategically choosing activities that focus on muscle hypertrophy in the forearm and force production in the lower leg may be the optimal path to follow when designing an intervention to improve bone strength in children.

5.2 Strengths and Weaknesses

A particular strength of this study was that it explored associations across a variety of bone and neuromuscular properties. By using an exploratory analysis, our findings guide future studies in terms of specific bone properties to focus on. We also provided evidence warranting more research into pre-pubertal sex specific bone properties.

Another strength of this study was that only a single technician was used for each of the three measurement modalities. Therefore, there are no inter-technician errors to be concerned with. On the note of intra-technician precision errors, using the pQCT, bone properties can be imaged in children with precision errors comparable to those reported in older adults in our lab (e.g. CV% at the radius 1.4 to 6.1 %, CV% at the tibia 0.7 to 2.1) (Duckham et al. 2013; Duff et al., 2015). Our lab is also currently assessing HR-pQCT precision errors in children, and results from this study should be available in Spring 2016. Precision of the force measurements is also currently underway and results from this analysis should be available in Spring 2016.

When participants were in the kinematics lab, their movements were standardized as much as possible. If they were not able to perform a movement (e.g. a push-up) on the first try following the explanation and demonstration, a second demonstration was given. Participants were also prompted during movements (push-ups) to help maintain the proper body positioning and motion throughout the entire length of the movements. This control, however subjective, was also a strength of the study.

A weakness of this study was our limited ability to evaluate the effort and technique of the participant during neuromuscular performance testing. Not performing with maximal effort may lead to a measurement that does not fully reflect the loading strains placed on the bones during daily activities of a similar nature. The same instruction and encouragement was given to participants throughout testing; however, some participants were much more intrinsically motivated. For example, some participants complained even prior to the start of any force testing that they didn't like push-ups, or could not do push-ups, while others were excited to see how many they could do. Not only did the effort put in affect the measurements, but the ability to perform specific tasks (e.g. maximal push-up) also varied greatly between participants. Some participants had no problem doing upwards of fifteen push-ups in a row and some could barely do a single push-up. Using the current protocol, it was difficult to track how well a participant could perform a movement.

This study was limited by its cross-sectional design and small sample size. A longitudinal study spanning the few years prior to peak height velocity may have allowed for a more comprehensive view of the adaptations in bone properties and strength in association with neuromuscular performance. In addition, sample size small and limited adjustment of associations for other determinants of bone properties, such as nutritional factors. For example, protein and calcium intake, along with other vitamins and minerals has been shown to affect bone content in the growing skeleton (New & Bonjour, 2003). Larger samples sizes are required to address these factors in future studies.

5.3 Future Directions

This study has many directions it can travel that will improve the consistency of the data collected in the kinematics lab, and expand the scope of the information collected.

5.3.1 Marker Placement

We used a single marker, placed between the top of the shoulder blades, to track the movement of the participant in the lab. This single marker was used to identify the stages of the push-ups, and the information it provided helped in the data processing portion of analysis. By increasing the number of markers placed on the participant, it will be possible to better track the participant’s movement while doing specific tasks. It is suggested that the original marker be kept in the same location between the shoulder blades, and that additional markers be placed on top of the shoulders, on the forearms and hands, at the lumbar spine, and on the heels. These additional markers will allow a participant’s body position to be tracked as they perform the movement. It will be possible to see the flexion and extension of the back during a push-up, and it will also make it possible to track the flexion angle of the elbow. Both of these are performance markers that can be rated so as to rank each participant’s ability.

5.3.2 pQCT Image Rating Scale

Children are inherently fidgety and, as such, obtaining scans that were able to be analyzed was difficult. The need to repeat a scan for both pQCT and HR-pQCT was determined objectively by the technicians. A specific criteria of “no breaks in the bone” for the pQCT and a rating of 3 or lower according to the Xtreme CT Manual; (Scanco Medical, Switzerland) was used to determine if a scan was usable or not. Blew et al. (2014) created a rating scale for pQCT images (Fig 16) that was rarely usable for the children’s scans. The problem with the Blew rating scale being used in this study is that if we removed all scans rated as a five based on Blew’s scale, we would remove over half of the images. By creating a scale used for the rating of child scans specific to bone (excluding muscle), it will be easier to rate scans consistently, and to make the decision of rescanning easier for the technicians. An image scale for this purpose will be focused on bone descriptors, (e.g. the bone contour is intact). It may be necessary to create a second rating scale that focuses more on muscle parameters, (e.g. there is no streaking (movement artifact) in the muscle), and to have a compilation of these scores used in order to rate whole scans. It may be possible to use these rating scales for adult scans, but it will be more beneficial to base the scales on children's scans due to the increased amount of movement seen in children's scans.

5.3.3 Designing an Intervention

These preliminary observations highlight the need for further larger investigations on neuromuscular performance and bone properties and strength in order to be able to create an effective intervention for school aged children to improve their bone health. Research that includes testing the associations between bone strength in children and more irregular daily activities (e.g. donkey kicks) as well as play structure usage would be beneficial in determining the best activities for an intervention.

5.4 Summary

This study provided insight into the bone-muscle relationship by associating neuromuscular performance with bone architecture in the forearm and lower leg in children. In the forearm, muscle area and grip strength predominantly predicted bone outcomes (6-22%), suggesting that activities that focus on muscle hypertrophy and gripping should be included in any intervention created. In the tibia, components of both countermovement and standing long jumps independently predicted 6-10% of variance in bone properties and strength. The evidence presented in this thesis suggests that more research is needed in order to determine the best activity for optimizing bone health in children. However, a start can be made in designing an intervention that includes grip training and impact loading activities.

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APPENDIX A

Appendix A

Dear Parent/Guardian,

On behalf of the Bone Imaging Research Group at the University of Saskatchewan, we would like to provide you with information about our proposed investigation related to bone health in children. We kindly ask you to consider allowing your child to participate in our investigation study.

We are studying the role physical activity plays in determining bone structure and strength in the forearm and lower leg bones in children. Our motivation to do this research is related to fracture prevention in children. Forearm fractures are the most common type of pediatric fracture and more children suffer from fractures now than in previous decades. Reasons for the increased incidence in pediatric fractures are unknown. Our research aims to characterize lifestyle factors that can be used to optimize bone strength development during growth. We hope that the information gained could enhance fracture prevention in childhood and perhaps have long-term benefits in osteoporotic fracture prevention. To address our research objective, we are aiming to recruit 130 children, girls and boys 8-14 years of age, to participate in this study.

Your child's participation would be voluntary and you would be free to withdraw your child at any time without giving any reason for your decisions. If you do not wish to have your child participate, you or your child would not lose any status or benefit within the University of Saskatchewan.

Study measurements would take approximately 2 hours after school. There is also opportunity for testing sessions on the weekend. We would provide transportation in a taxi cab and a nutritious snack for your child prior to measurements. An adult researcher from the study will be with your child at all times, including during the transportation to and from the study. However, if you so choose, you can drive your child to and from the testing session.

The measurements that we will perform in the study are two bone imaging procedures and some physical performance measurements. You will find enclosed a copy of our parent/legal guardian consent form, which provides a more detailed description of the study protocols. We have also included a copy of a child's assent form, which describes the study in terms that is more easily understood by your child. You will also receive two questionnaires that we ask be completed prior to coming in for testing.

If you and your child are interested in participating in our study please sign both the consent and assent forms as well as complete the contact information and have your child return them to his or her teacher. If you have any questions regarding this study, please contact us via email or phone. Our contact information is provided below.

On behalf of our research team we would like to thank you for consideration.

Sincerely,

Dr. Saija Kontulainen
Phone: (306) 966-1077
Email: saija.kontulainen@usask.ca

Kelsey Björkman (MSc Student)
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Appendix A

Parental Information and Consent Form

Study Title: The Association between Physical Activity in Childhood and Bone Strength in Forearm and Lower Leg Bones

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Sponsor: Saskatchewan Health Research Foundation

INTRODUCTION

Your child is invited to take part in this research study because we want to assess the relationship between bone strength and physical activity in children. We will examine the association of different types of physical activities and bone strength development in forearm and lower leg bones.

Your child's participation is voluntary. It is up to you to decide whether or not you wish to have him or her participate. If you wish to have him or her participate, you will be asked to sign this form. If you decide to have your child take part in this study, you are still free to withdraw him or her at any time without giving any reason for your decision.

If you do not wish to have your child participate, you will not lose any benefits within the College of Kinesiology to which you are entitled to or are presently receiving. It will not affect your relationship with your teachers, researchers or anyone involved in the study.

Please take the time to read the following information carefully. You can ask the researcher to explain any words or information that you do not understand. You may ask as many questions as you need. Please feel free to discuss this with your family, friends or family physician before you decide.

WHO IS CONDUCTING THE STUDY?

Funding for this study comes from Saskatchewan Health Research Foundation, which will reimburse costs related to data collection and analysis. In addition, this grant will provide funds for snacks and small gifts for participants. Neither the institution nor any of the investigators or staff will receive any financial benefit for conducting this study.

WHY IS THE STUDY BEING DONE?

This study is being done because we want to better understand the role physical activity and muscle strength plays in bone structure, density and strength in the growing skeleton. This information will help to assess the underlying reasons for fractures that are common in children. Previous research has demonstrated that low bone mass increases risk of fracture in both boys and girls. Research has also shown that vigorous physical activity increases bone mass in those bones and bone sites which experience forces during physical activities. However, it is poorly understood if physical activities and performance can influence bone structure, density and estimated strength in the upper arm and lower leg bones during growth. Therefore, the purpose of this study is to examine site-specificity (arm versus leg) in the relationship between imaged bone strength measures and physical activity in children by comparing the association of different types of physical activities and bone properties in the forearm and lower leg bones.

WHO CAN PARTICIPATE IN THIS STUDY?

Your child is eligible to participate in this study if she or he is between the ages of 8 and 14 years old, have obtained parental/guardian consent, and is without previous fractures or any disease known to affect bone or muscle health.

WHAT DOES THE STUDY INVOLVE?

The total time requirement for participation is 1.5 hours.

A. Testing Procedure:

Prior to measurement session at the College of Kinesiology:

1. You will receive two questionnaires in your recruitment package. These questionnaires are to be completed with parent/guardian. The first questionnaire is a seven-day-recall, Physical Activity Questionnaire for Children. In addition you will be asked to specify the amount of participation (times per year) in activities/sports that load the forearm (such as gymnastics, wrestling, or baseball). The second questionnaire is regarding background information, such as your child's handedness and fracture history. The questions related to health are for inclusion/exclusion criteria only (for example, previous fracture history, medication use, such as corticosteroids that may affect bone health). The question related to ethnicity is used only as a descriptive characteristic of the study population.

2. The two questionnaires will be collected at the time of data collection at the University of Saskatchewan. In the event that a questionnaire(s) is (are) not returned or fully completed a research assistant may contact you to conduct a phone interview. Please see the contact information sheet at the end of this consent form.

Measurement session at College of Kinesiology:
Below is a detailed description of the testing procedures:

1. Your child's dominant forearm (the arm that he or she uses to perform daily tasks e.g., writing and brushing teeth) will be scanned with Peripheral Quantitative Computed Tomography (pQCT), a bone imaging tool, at two sites: on the wrist and one scan from the forearm. His or her dominant lower leg (the leg that he or she uses to performing daily tasks e.g., first step when walking up stairs) will be scanned at sites: at the ankle and one scan at the site that corresponds with 2/3 of the leg length. A total of 4 scans will be performed with pQCT with each scan taking approximately 2-4 minutes for each site.

2. Your child's dominant wrist and ankle will be scanned with a high-resolution pQCT (HR-pQCT). A total of two scans will be performed with HR-pQCT with each scan taking approximately 3 minutes for each site.

3. Your child's hand strength will be measured using a special device called a handheld dynamometer. Your child will be asked to squeeze the special device as hard as he or she can for 3 seconds.

4. Your child's upper arm strength and endurance will be assessed by two maximal push-up tests with their hands and toes using two different hand positions.
    a. Your child's movements during the push-ups will be recorded by a specialized motion capture system which tracks small plastic reflective spheres attached to your child's back using hypoallergenic tape.
    b. Your child will be instructed to perform as many push-ups with hands positioned on a special device designed to measure the force of each push-up
    c. Your child will also perform three half push-ups going from the lowered to raised position as fast as they can

5. Your child's upper arm strength and endurance will be assessed by two maximal push-up tests with their hands and knees (tracked with the same reflective plastic spheres as above) using two different hand positions.
    a. Your child will be instructed to perform as many push-ups with hands positioned on a special device designed to measure the force of each push-up
    b. Your child will also perform three half push-ups going from the lowered to raised position as fast as they can

6. Your child's leg strength and power will be measured by asking your child to perform two jumping tests.
    a. The first jumping test is a standing long jump, in which your child will be asked to jump as far forward as he or she can. Your child

will be asked to perform this jump three times, with an appropriate rest period given between each trial.
b. The second jumping test is a countermovement jump test. Your child will be asked to jump up as high as possible and land on special force platform designed to measure the force of the jump. These force platforms are recessed into the floor such that they are flush with the floor surface, posing no hazard to your child. Your child will be asked to perform this jump three times, with an appropriate rest period given between each trial.

7. Your child will be fitted with an Actical Accelerometer, which is a small device that is worn on your child’s right hip. This will be worn for seven days and will record your child’s physical activity levels during the week. An instruction sheet will be sent home with each child. A research assistant will collect the accelerometer seven days after the testing session.
8. Your child will also receive a third and final questionnaire, which details nutritional intake. This questionnaire will be collected within a week at the same time as the accelerometer.

A small meal is provided from Subway during the course of this testing period. Please see the menu option form at the end of this questionnaire. This testing session at the College of Kinesiology will take approximately 1.5hours.

You are welcome to attend and watch the testing session. However, it is not mandatory that you attend the testing session with your child. There is the option to have your child driven home using a taxi cab service following testing. Your child will always be accompanied by an adult research assistant, including during transportation following testing. If you wish to have your child driven home following testing, please complete the driving waiver found attached to this consent form.

WHAT ARE THE BENEFITS OF PARTICIPATING IN THIS STUDY?
If you choose to have your child participate in this study, he or she may not directly benefit. However, you will be provided with images of the bones and muscles scanned and results from the performance measures, should you request them. This information is used to answer the research question and cannot be used for diagnostic purposes of bone or muscle health. It is hoped that the information gained from this study can be used to design physical activity interventions that would aim to strengthen forearm bone sites vulnerable to fracture in children. Knowledge gained from this study may provide essential information that can be applied to the therapy of children with musculoskeletal problems and public health initiatives (e.g., Canadian Physical Activity Guides for Children and Youth) to prevent forearm fractures and to optimize bone strength development in children and adolescents.

ARE THERE POSSIBLE RISKS AND DISCOMFORTS?

If you choose to have your child participate in this study there is a minor risk that involves exposure to small amounts of radiation during the pQCT and HR-pQCT scans. The total amount of radiation your child will be exposed to is very low, an average less than 10μSv for two scanning methods. If we need to repeat a scan due to movement artifact we will do so only once. The maximum effective dose of radiation will be 12μSv. This dose is comparable to the amount of background radiation a person receives in two weeks from naturally occurring sources in Saskatchewan. For reference, a cross-country flight could expose a person to about 30μSv of radiation (http://www.hc-sc.gc.ca/hc-ps/ed-ud/respond/nuclea/measurements-measures-eng.php).

WHAT IF NEW INFORMATION BECOMES AVAILABLE THAT MAY AFFECT MY DECISION TO PARTICIPATE?

Researchers and research assistants will provide you with an image and description of your child's bone scans and information on how your child's performance measures compared to the published reference data at the second measurement time. If there is any information in the first scan or performance measures that warrants further attention we will inform you at the second measurement time.

WHAT HAPPENS IF I DECIDE TO WITHDRAW?

Your decision to have your child participate in this research is voluntary. You may withdraw him or her from the study at any time. You do not have to provide a reason. There will be no penalty or loss of benefits if you choose to withdraw. Your future relationships within the College of Kinesiology will not be affected.

If you choose to have your child enter the study and then decide to withdraw him or her later, all data collected about him or her during enrolment will be retained for analysis.

WILL I BE INFORMED OF THE RESULTS OF THIS STUDY?

After your child's participation, the results of your child's grip strength, push-up, and standing long jump test results compared to normative referenced data will be emailed to you if you wish to receive this information. Results of the study objectives, the accuracy, and precision of pQCT measurement, will also be emailed to you if you wish to receive this information.

WHAT WILL THIS STUDY COST ME?

You will not be charged for any research-related procedures. You will not be paid for participating in this study. You will not receive any financial benefits for being in this study, or as a result of data obtained from research conducted under this study. Your child will be provided with a selection of small toys and items such stickers, pins, and hairclips to select after the measurements.

WHAT HAPPENS IF SOMETHING GOES WRONG?

If an adverse event related to the study occurs, trained staff will be available throughout the conduct of the study who can respond immediately. Necessary medical treatment will be made available at no additional cost to you. As soon as possible, notify the research team. By signing this document, you do not waive any of your legal rights.

WILL MY TAKING PART IN THIS STUDY BE KEPT CONFIDENTIAL?
In Saskatchewan, The *Health Information Protection Act (HIPA)* defines how the privacy of your child's personal health information must be maintained so that his or her privacy will be respected.

Your child's confidentiality will be respected. No information that discloses your child's identity will be released or published without your specific consent to the disclosure. A special number (which will not include his or her initials, date of birth, name or address) will be used. Your child's study records, including his or her questionnaire and scan information will be kept for 5 years in a locked cabinet in Dr. Kontulainen's office at the College of Kinesiology. Your child's information and results of the study will also be recorded in a computer database. Only the investigators and research assistants will have access to these study records. However, research records and medical records identifying your child may be inspected in the presence of Dr. Kontulainen or her designate by a representative of the University of Saskatchewan Research Ethics Board for the purpose of monitoring the research. However, no records, which identify your child by name or initials, will be allowed to leave Dr. Kontulainen's office. The results of this study may be presented in a scientific meeting or published, but your child's identity will not be disclosed.

WHO DO I CONTACT IF I HAVE QUESTIONS ABOUT THE STUDY?
If you have any questions or desire further information about this study before or during participation, you can contact Dr. Saija Kontulainen at (306) 966-1077 or by e-mail at saija.kontulainen@usask.ca.

If you have any concerns about your child's right as a research participant and/or your experiences while participating in this study, contact the Chair of the University of Saskatchewan Research Ethics Board, at (306) 966-2975 (out of town calls 1-888-966-2975). The Research Ethics Board is a group of individuals (scientists, physicians, ethicists, lawyers, and members of the community) that provide an independent review of human research studies. This study has been reviewed and approved on ethical grounds by the University of Saskatchewan Research Ethics Board.

ARE THERE ADDITIONAL TESTING OPPORTUNITES?

Your child is also invited to participate in the precision testing portion of this study. What this means is that we require some participants to return to the College of Kinesiology within one week of the original testing date to repeat the testing procedure so that we can ensure our measurements are to the highest possible caliber for all participants. All testing procedures will be the same as the original baseline testing. Please indicate your interest in the precision portion of the study on the attached consent and assent forms.

Appendix A

CONSENT TO PARTICIPATE

Study Title: The Association between Physical Activity in Childhood and Bone Strength in Forearm and Lower Leg Bones

- I have read (or someone has read to me) the information in this consent form
- I understand the purpose, procedures and possible risks and benefits of the study
- I was given sufficient time to think about it
- I had the opportunity to ask questions and have received satisfactory answers
- I understand that I am free to withdraw my child from this study at any time for any reason and the decision to stop taking part will not affect my future relationships
- I give permission to the use and disclosure of my child's de-identified information collected for the research purposes described in this form
- I understand that by signing this document I do not waive any of mine or my child's legal rights
- I will be given a signed copy of this consent form

I agree to have my child participate in this study.

Printed Name of Child Participant: ____

Printed Name of Parent/Guardian: ____

Signature of Parent/Guardian: ____
Date: (DD/MM/YY): ____/_____/____

Printed Name of Person Obtaining Consent: ______________________________

Signature of Person Obtaining Consent: __________________________________
Date: (DD/MM/YY): ____/_____/____

I agree to have my child wear an accelerometer for seven days following testing at the College of Kinesiology at the University of Saskatchewan.

Yes No

I agree to have my child's photo taken for the purpose of being published with the data collected. My child's face will be censored and unrecognizable to the public.

Yes No

I agree to have my child return to the College of Kinesiology for repeat testing within one week of the original testing date.

Yes No

Appendix A

Child Assent Form

Study Title: The Association between Physical Activity in Childhood and Bone Strength in Forearm and Lower Leg Bones

Principal Investigator: Dr. Saija Kontulainen, Associate Professor
College of Kinesiology, University of Saskatchewan
87 Campus Drive, Saskatoon SK S7N5B2 Canada
Telephone: (306) 966-1077
Fax: (306): 966-6464
Email: saija.kontulainen@usask.ca

Student Researcher: Kelsey Björkman (MSc Student)

INTRODUCTION

We are inviting you to be a part of our study that looks at the strength of your bones and muscles. This study will help us learn how well two imaging tools measure the bones and muscles in your arm and leg. We will compare your bones and muscles with how strong and active you are. This will help us learn if there is a connection between how strong your bones and muscles are and how active you are.

WHAT HAPPENS IN THIS STUDY?

Before you come to the College of Kinesiology for this study:

1. You will get two questionnaires that you will take home and fill out with your parent or guardian.

When you come to the College of Kinesiology for this study:

1. When you arrive at the College of Kinesiology you will get a small meal from Subway before you start the study
2. During this study, a researcher will measure your arm and leg using two special imaging machines. These machines create images of your arm and leg bones and muscles that help the researcher learn how strong your bones and muscles are
3. After you have been measured by these machines a researcher will stick some small shiny spheres to your back so that our special cameras can see how you move and ask you to perform five different activities:
    a. You will be asked to squeeze a special handheld device as hard as you can for three seconds
    b. You will be asked to place your hands on a special force platform that is in the floor and perform a push-up from your hands and toes as fast as you can. This test will measure the strength of your arms
    c. You will be asked to do the same push-up test again but we will change where your hands are on the floor.
    d. You will be asked to place your hands on the same special force platform and perform a push-up from your hands and knees as fast as you can

e. You will be asked to do the same push-up test again, but we will change where your hands are on the floor.
f. You will be asked to jump forward as far as you can
g. You will be asked to place your hands on the special force platform that is in the floor and to perform as many push-ups as you can from your hands and toes
h. You will be asked to place your hands on the same special force platform in the floor and to perform as many push-ups as you can from your hands and knees
i. You will be asked to jump as high as you can. This test will also be performed on the special force platform that will measure how much force you can create

4. After completing these activities a researcher will give you a small device (motion sensor) that you will wear on your right hip for a full week. This small device can be worn under your clothes and will measure your activity
5. You will also get a third questionnaire to take home to fill out with your parent/guardian. This questionnaire will ask you questions about the food you normally eat.
6. At the end of testing a researcher will drive you either back to your home or your parent/guardian will pick you up

WILL YOU HAVE TO ANSWER ALL QUESTIONS AND DO EVERYTHING YOU ARE ASKED TO DO?

It is your choice whether you choose to answer our questions. It is also your choice to choose if you want to have the scans or participate in the five activities and you won't have to do it if you don't want to. If you do not want to do a part of the study you can tell the researcher that you do not want to. You will not get in trouble if you choose not to do something in this study.

WHO WILL KNOW THAT YOU ARE IN THE STUDY?

Your name will not be on any of the information that you give us or that we collect from you. No one will know that the information from our study came from you.

We will not let anyone see your answers or any of your other information. Your teachers, parents, and classmates will not see your results.

DO YOU HAVE TO BE IN THIS STUDY?

You can be in this study if you want to, but you don't have to. This study is not part of your schoolwork and it is your choice to participate. Even if you decide to be a part of the study now, you can change your mind later. You just have to say that you do not want to be a part of the study anymore. If you decide not to be a part of the study no one will get angry or upset with you. If you choose not to be in this study it will not affect your ability to participate in school activities or other activities at the University of Saskatchewan.

CAN YOU BE IN THE STUDY MORE THAN ONCE?
You can come back to the University one week after the first test to be tested again if you would like. We need some of the participants to be tested twice so that we can see how well we measured you the first time. This is an important part of the study for us as researchers, and you coming back would help us very much.

DO YOU HAVE ANY QUESTIONS?
You can ask questions at any time. You can ask now or you can ask later. You can talk to me or you can talk to someone else at any time during the study.

CONSENT TO HAVE MY PICTURE TAKEN
It is okay for my picture to be taken when I am being tested so that the researchers can use them to show others what kinds of tests I did. No one will be able to see my face in the pictures, so they won't know it is me.

Yes No

CONSENT TO COME BACK
I would like to come back for testing again one week after the first test?

Yes No

CONSENT TO PARTICIPATE
I have talked with my parents/guardians about this study and I understand what I will be asked to do. I know I can stop being in this study at any time and I will not get in trouble. I have had the chance to ask questions and all of my questions were answered in a way that I understood.

Name (Printed) **Signature**

______________________________ ______________________________

Today's Date (MM/DD/YY): _____/_____/_____

Witness Name (Printed) **Witness Signature**

______________________________ ______________________________

Today's Date (MM/DD/YY): _____/_____/_____

APPENDIX B

Appendix B

Dear Parent/Guardian,

On behalf of the Bone Imaging Research Group at the University of Saskatchewan, we would like to provide you with information about our proposed investigation related to bone health in children. We kindly ask you to consider allowing your child to participate in our investigation study.

We are studying the role physical activity plays in determining bone structure and strength in the forearm and lower leg bones in children. Our motivation to do this research is related to fracture prevention in children. Forearm fractures are the most common type of pediatric fracture and more children suffer from fractures now than in previous decades. Reasons for the increased incidence in pediatric fractures are unknown. Our research aims to characterize lifestyle factors that can be used to optimize bone strength development during growth. We hope that the information gained could enhance fracture prevention in childhood and perhaps have long-term benefits in osteoporotic fracture prevention. To address our research objective, we are aiming to recruit 80 children, girls and boys 8-14 years of age, to participate in this study.

Your child's participation would be voluntary and you would be free to withdraw your child at any time without giving any reason for your decisions. If you do not wish to have your child participate, you or your child would not lose any status or benefit within the University of Saskatchewan.

Study measurements would take approximately 2 hours after school. There is also opportunity for testing sessions on the weekend. We would provide transportation in a taxi cab and a nutritious snack for your child prior to measurements. An adult researcher from the study will be with your child at all times, including during the transportation to and from the study. However, if you so choose, you can drive your child to and/or from the testing session.

The measurements that we will perform in the study are two bone imaging procedures and some physical performance measurements. If you and your child are interested in participating in our study please contact study coordinator (kelsey.bjorkman@usask.ca) or fill out the attached request for information page and have your child return it to his or her teacher. If you have any questions regarding this study, please contact us via email or phone. Our contact information is provided below.

On behalf of our research team we would like to thank you for consideration.

Sincerely,

Dr. Saija Kontulainen
Phone: (306) 966-1077
Email: saija.kontulainen@usask.ca

Kelsey Björkman (MSc Student)
Phone: (306) 715 7886
Email: kelsey.bjorkman@usask.ca

Contact Information

We, ____(please print your name) and my child, ______________________________(please print name) are interested in participating in and/or receiving more information about the Bone Health Study being conducted at the University of Saskatchewan.

Contact Information

First Name: _________________________________

Last Name:__________________________________

Relation to Child:______________________________

Phone Number: ______________________________

E-mail:______________________________________

I would prefer to be contacted by (please circle):

Phone Email

Signature of Parent/Guardian: ______________________________________

Date: _____/_____/_____ (DD/MM/YY)

APPENDIX C

Appendix C

Physical Activity Questionnaire (Elementary School)

For Bone Strength Study

Name__________________ Age________

Sex M______ F______ Grade_______

Teacher:_______________________

We are trying to find out about your level of physical activity from ***the last 7 days*** (in the last week). This includes sports or dance that make you sweat or make your legs feel tired, or games that make you breathe hard, like tag, skipping, running, climbing, and others.

Remember:

There are no right and wrong answers — this is not a test.
Please answer all the questions as honestly and accurately as you can — this is very important.

1. Physical activity in your spare time: Have you done any of the following activities in the past 7 days (last week)? If yes, how many times? (Mark only one circle per row.)

	No	1-2	3-4	5-6	7 or more times
	○	○	○	○	○
Skipping	○	○	○	○	○
Rowing/canoeing	○	○	○	○	○
In-line skating	○	○	○	○	○
Tag	○	○	○	○	○
Walking for exercise	○	○	○	○	○
Bicycling	○	○	○	○	○
Jogging or running	○	○	○	○	○
Aerobics	○	○	○	○	○
Swimming	○	○	○	○	○
Baseball, softball	○	○	○	○	○
Dance	○	○	○	○	○
Football	○	○	○	○	○
Badminton	○	○	○	○	○
Skateboarding	○	○	○	○	○
Soccer ....………..	○	○	○	○	○
Street hockey	○	○	○	○	○
Volleyball	○	○	○	○	○
Floor hockey	○	○	○	○	○
Basketball	○	○	○	○	○
Ice skating	○	○	○	○	○
Cross-country skiing	○	○	○	○	○
Ice hockey/ringette	○	○	○	○	○
Gymnastics...	○	○	○	○	○
Martial Arts..	○	○	○	○	○
Wrestling..	○	○	○	○	○

Other: ________________________

2. In the last 7 days, during your physical education (PE) classes, how often were you very active (playing hard, running, jumping, throwing)? (Check one only.)

I don't do PE .... ○
Hardly ever .... ○
Sometimes .... ○
Quite often .... ○
Always .... ○

3. In the last 7 days, when you were active, how often did you use your hands for pushing, climbing, or throwing? (Check only one.)

I only use my legs .... ○
Hardly ever.................. .... ○
Sometimes .... ○
Quite often .... ○
Always .... ○

4. In the last 7 days, what did you normally do *at lunch* (besides eating lunch)? (Check one only.)

Sat down (talking, reading, doing schoolwork)…..... ○
Stood around or walked around .... ○
Ran or played a little bit .... ○
Ran around and played quite a bit .... ○
Ran and played hard most of the time .... ○

5. In the last 7 days, on how many days *right after school*, did you do sports, dance, or play games in which you were very active? (Check one only.)

None .... ○
1 time last week .... ○
2 or 3 times last week .... ○
4 times last week .... ○
5 times last week .... ○

6. In the last 7 days, on how many *evenings* did you do sports, dance, or play games in which you were very active? (Check one only.)

None .... ○
1 time last week .... ○
2 or 3 times last week .... ○
4 or 5 last week .... ○
6 or 7 times last week .... ○

7. *On the last weekend*, how many times did you do sports, dance, or play games in which you were very active? (Check one only.)

None .... ○
1 time .... ○
2 — 3 times .... ○
4 — 5 times .... ○
6 or more times .... ○

8. Which *one* of the following describes you best for the last 7 days? Read *all five* statements before deciding on the *one* answer that describes you.

F. All or most of my free time was spent doing things that involve little physical effort

G. I sometimes (1 — 2 times last week) did physical things in my free time (e.g. played sports, went running, swimming, bike riding, did aerobics)

H. I often (3 — 4 times last week) did physical things in my free time

I. I quite often (5 — 6 times last week) did physical things in my free time

J. I very often (7 or more times last week) did physical things in my free time

9. Mark how often you did physical activity (like playing sports, games, doing dance, or any other physical activity) for each day last week.

	None	Little Bit	Medium	Often	Very Often
Monday	○	○	○	○	○
Tuesday	○	○	○	○	○
Wednesday	○	○	○	○	○
Thursday	○	○	○	○	○
Friday	○	○	○	○	○
Saturday	○	○	○	○	○
Sunday	○	○	○	○	○

10. Were you sick last week, or did anything prevent you from doing your normal physical activities? (Check one.)

Yes .... ○
No .... ○

If Yes, what prevented you? ___________________________________

Appendix C

11. Please list any sports or physical activities that involve using your hands or arms you have participated in regularly. Please tick the boxes to indicate how old you were for each sport/activity and how many years you participated for.

	Age:																	
Activities:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

12. Please list any sports or physical activities that involve using your hands or arms you have participated in regularly during the **<u>last 12 months</u>** and indicate the average frequency of the activity (sessions/week).

Activity:____

Sessions/week: _______

Activity:____

Sessions/week: _______

Activity:____

Sessions/week: _______

Activity:____

Sessions/week: _______

Activity:____

Sessions/week: _______

APPENDIX D

Name:_______________________ **Subject ID:**_____________________

Date:____/____/_____(DD/MM/YY)

Limb Dominance, Medication, and Health Questionnaire

Please answer the following questions to the best of your ability. You may also choose not to answer any of these questions.

1. Which is your dominant hand (e.g., which hand do you write with)?

Right
Left
I am mix-handed
I don't know

2. Which is your dominant leg (e.g., which leg do you use to kick a ball)?

Right
Left
I am mix-legged
I don't know

3. Are you taking any prescription medications?

Yes
No
Not Sure

If *yes*, how many prescription medications are you taking? _______

Name:____________ Name:____________
Name:____________
Dosage:___________ Dosage:___________
Dosage:___________

4. Are you taking any over-the-counter medications?

Pain killers, antacids, allergy pills, and hydrocortisone creams are all examples of over the-counter medications.

Yes
No
Not Sure

If *yes*, how many over-the-counter medications are you taking? _______

Name:____________ Name:____________
Name:____________
Dosage:___________ Dosage:___________
Dosage:___________

5. Have you ever had a wrist fracture?

Yes
No
Not Sure

If *yes*, please indicate the side and date of the fracture:

Left or Right (Please circle) Date: (MM/YY): _____/_____

6. Have you ever had any other broken bones or stress fractures?

Yes
No
Not Sure

If *yes,* please indicate the bone, the side and the date of break/stress fracture:

Bone:_______________

Left or Right (Please circle) Date: (MM/YY): _____/_____

7. Have you ever been treated or diagnosed with arthritis or other joint or bone disease?

Yes
No
Not Sure

If *yes*, please explain:

____
____

_ _

The following question is for female participants only

Have you started menstruating?

Yes
No

If yes, what was the date of your first period?

____

Appendix D

The following questions are for the parents/guardians of the participant:

10. Where were you born?

Mother:______________________ Father:_______________________

11. Where were your parents born?

Maternal Mother:______________ Maternal Father:______________________

Paternal Mother:______________ Paternal Father:______________________

12. How long has your family lived in North America? Years:____ Months:____

13. Where did your family live before moving to North America?
____

14. How would you classify your family ethnically? (I.e. Caucasian-Canadian, Japanese-Canadian, etc.)
____

Thank you for taking the time to complete this questionnaire.

APPENDIX E

Appendix E

	WITH			WITHOUT		
	Shapiro-Wilk			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
BSIc	.964	43	.198	.968	42	.289
RS_ToC	**.930**	**43**	**.012**	.973	42	.408
RS_ToD	.982	43	.719	.973	42	.426
RS_ToA	.975	43	.473	.973	42	.418
RS_CrtC	**.907**	**43**	**.002**	.986	42	.886
RS_CrtD	.993	43	.997	.988	42	.927
RS_CrtA	.965	43	.220	.979	42	.638
SSIp	**.934**	**43**	**.015**	.955	42	.095
FAM_TOT_A	**.832**	**43**	**.000**	.976	42	.525
BSIc Tib	.983	43	.750	.976	42	.499
TS_TOT_CNT	**.777**	**43**	**.000**	.969	42	.304
TS_TOT_DEN	**.927**	**43**	**.009**	**.926**	**42**	**.010**
TS_TOT_A	.974	43	.416	.981	42	.708
TS_CRT_CNT	**.704**	**43**	**.000**	.983	42	.787
TS_CRT_DEN	.975	43	.461	.987	42	.897
TS_CRT_A	**.824**	**43**	**.000**	.976	42	.528
TS_RP_CM_W	**.734**	**43**	**.000**	**.936**	**42**	**.021**
LLM_TOT_A	**.891**	**43**	**.001**	.948	42	.057
Total-Area T	.971	43	.355	.974	42	.434
CortArea1 T	**.833**	**43**	**.000**	.952	42	.074
TrabArea1 T	.975	43	.479	.977	42	.553
D100-1 T	.963	43	.173	.960	42	.145
Dcomp1 T	**.911**	**43**	**.003**	.950	42	.066
Ct.Th1 T	**.861**	**43**	**.000**	**.913**	**42**	**.003**
Dtrab1 T	.962	43	.158	.964	42	.212
tBV/TV1 T	.961	43	.149	.964	42	.198
tTb.N1 T	.977	43	.520	.976	42	.518
tTb.Th1 T	.985	43	.849	.986	42	.872
Total-Area R	.971	43	.337	.960	42	.151
CortArea1 R	**.849**	**43**	**.000**	**.888**	**42**	**.001**
TrabArea1 R	.958	43	.119	.960	42	.152
D100-1 R	.960	43	.141	.953	42	.085
Dcomp1 R	.977	43	.522	.975	42	.465
Ct.Th1 R	**.918**	**43**	**.005**	**.936**	**42**	**.021**
Dtrab1 R	.966	43	.221	.968	42	.292
tBV/TV1 R	.966	43	.229	.969	42	.301
tTb.N1 R	.954	43	.087	.956	42	.109
tTb.Th1 R	**.874**	**43**	**.000**	.874	42	**.000**
Score	.975	43	.469	.971	42	.361

A Shapiro Wilk's test for normality, with and without a single outlier. Bolded values are significant.

APPENDIX F

Appendix F

The following tables include the full set of linear regression models built for the purpose of this thesis. They show the base model, overall R^2, change in R^2, partial r, partial R^2, beta and *p* values. All models returning a significant result are bolded below.

Appendix F

Distal Radius: Total Area

	Independent Variables	Overall R2	R2 Change	partial r	Partial R2	Beta	p-value
Base		0.312					
	Sex			0.328	0.108	0.278	0.023
	Maturation			0.236	0.056	0.313	0.107
	Weight			0.120	0.014	0.201	0.417
	Limb Length			0.036	0.001	0.067	0.810
Model 1		**0.425**	**0.115**				
	Sex			**0.204**	**0.042**	**0.160**	**0.169**
	Maturation			**0.275**	**0.076**	**0.333**	**0.062**
	Weight			**-0.190**	**0.036**	**-0.375**	**0.201**
	Limb Length			**0.093**	**0.009**	**0.159**	**0.535**
	Muscle Area			**0.427**	**0.182**	**0.605**	**0.003**
Model 2		0.345	0.008				
	Sex			0.338	0.114	0.287	0.022
	Maturation			0.232	0.054	0.292	0.121
	Weight			0.089	0.008	0.143	0.555
	Limb Length			0.075	0.006	0.138	0.618
	Physical Activity Score			0.118	0.014	0.094	0.434
Model 3		**0.453**	**0.114**				
	Sex			**0.367**	**0.135**	**0.282**	**0.008**
	Maturation			**0.090**	**0.008**	**0.103**	**0.554**
	Weight			**-0.071**	**0.005**	**-0.116**	**0.620**
	Limb Length			**0.114**	**0.013**	**0.194**	**0.426**
	Grip Strength (Mean)			**0.432**	**0.187**	**0.498**	**0.002**
Model 4		0.341	0.029				
	Sex			0.341	0.116	0.291	0.016
	Maturation			0.258	0.067	0.356	0.074
	Weight			0.194	0.038	0.372	0.182
	Limb Length			0.011	0.000	0.020	0.941
	Max Push-up Peak Force			-0.216	0.047	-0.256	0.136
Model 5		0.331	0.007				
	Sex			0.259	0.067	0.232	0.066
	Maturation			0.170	0.029	0.226	0.232
	Weight			0.091	0.008	0.154	0.524
	Limb Length			0.107	0.011	0.200	0.456
	Standard Push-Up Test #			0.108	0.012	0.093	0.450

Appendix F

Distal Radius: Cortical Area							
	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.358					
	Sex			0.240	0.058	0.192	0.100
	Maturation			0.189	0.036	0.240	0.200
	Weight			0.414	0.171	0.731	0.003
	Limb Length			-0.196	0.038	-0.361	0.182
Model 1		0.346	0.002				
	Sex			0.245	0.060	0.207	0.096
	Maturation			0.187	0.035	0.237	0.208
	Weight			0.364	0.132	0.807	0.012
	Limb Length			-0.201	0.040	-0.373	0.175
	Muscle Area			-0.058	0.003	-0.080	0.697
Model 2		0.372	0.004				
	Sex			0.151	0.023	0.120	0.316
	Maturation			0.201	0.040	0.246	0.181
	Weight			0.433	0.187	0.751	0.003
	Limb Length			-0.197	0.039	-0.361	0.188
	Physical Activity Score			0.087	0.008	0.068	0.565
Model 3		0.359	0.038				
	Sex			0.141	0.020	0.143	0.200
	Maturation			0.044	0.002	0.076	0.688
	Weight			0.241	0.058	0.556	0.032
	Limb Length			-0.114	0.013	-0.273	0.302
	Grip Strength (Mean)			0.195	0.038	0.288	0.079
Model 4		0.311	0.008				
	Sex			0.195	0.038	0.163	0.180
	Maturation			-0.037	0.001	-0.050	0.803
	Weight			0.298	0.089	0.601	0.038
	Limb Length			-0.061	0.004	-0.118	0.676
	Max Push-up Peak Force			0.116	0.013	0.138	0.428
Model 5		0.320	0.000				
	Sex			0.156	0.024	0.138	0.274
	Maturation			0.087	0.008	0.115	0.544
	Weight			0.385	0.148	0.704	0.005
	Limb Length			-0.123	0.015	-0.233	0.389
	Standard Push-Up Test #			0.013	0.000	0.011	0.930

Appendix F

Distal Radius: Trabecular Area

	Independent Variables	Overall R2	R2 Change	partial r	Partial R2	Beta	p-value
Base		0.214					
	Sex			0.284	0.081	0.253	0.051
	Maturation			0.193	0.037	0.271	0.189
	Weight			0.004	0.000	0.078	0.767
	Limb Length			0.072	0.005	0.143	0.629
Model 1		**0.327**	**0.117**				
	Sex			**0.159**	**0.025**	**0.134**	**0.285**
	Maturation			**0.225**	**0.051**	**0.292**	**0.128**
	Weight			**-0.234**	**0.055**	**-0.504**	**0.114**
	Limb Length			**0.127**	**0.016**	**0.236**	**0.394**
	Muscle Area			**0.403**	**0.162**	**0.611**	**0.005**
Model 2		0.249	0.008				
	Sex			0.302	0.091	0.272	0.041
	Maturation			0.186	0.035	0.248	0.216
	Weight			0.011	0.000	0.018	0.943
	Limb Length			0.111	0.012	0.219	0.461
	Physical Activity Score			0.105	0.011	0.090	0.487
Model 3		**0.348**	**0.095**				
	Sex			**0.324**	**0.105**	**0.267**	**0.020**
	Maturation			**0.067**	**0.004**	**0.089**	**0.641**
	Weight			**-0.133**	**0.018**	**-0.203**	**0.428**
	Limb Length			**0.136**	**0.018**	**0.253**	**0.342**
	Grip Strength (Mean)			**0.372**	**0.138**	**0.456**	**0.007**
Model 4		0.273	0.039				
	Sex			0.310	0.096	0.275	0.030
	Maturation			0.257	0.066	0.372	0.075
	Weight			0.149	0.022	0.299	0.306
	Limb Length			0.021	0.000	0.042	0.884
	Max Push-up Peak Force			-0.236	0.056	-0.294	0.103
Model 5		0.244	0.007				
	Sex			0.229	0.052	0.216	0.106
	Maturation			0.147	0.022	0.207	0.304
	Weight			0.025	0.001	0.045	0.860
	Limb Length			0.126	0.016	0.253	0.377
	Standard Push-Up Test #			0.104	0.011	0.095	0.468

Appendix F

Distal Radius: Total Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		-0.017					
	Sex			0.151	0.023	0.149	0.306
	Maturation			0.047	0.002	0.076	0.745
	Weight			0.152	0.023	0.317	0.293
	Limb Length			-0.089	0.008	-0.208	0.538
Model 1		-0.036	0.003				
	Sex			0.158	0.025	0.168	0.278
	Maturation			0.044	0.002	0.072	0.759
	Weight			0.153	0.023	0.413	0.293
	Limb Length			-0.094	0.009	-0.223	0.515
	Muscle Area			-0.058	0.003	-0.100	0.697
Model 2		0.028	0.016				
	Sex			0.121	0.015	0.119	0.423
	Maturation			0.080	0.006	0.119	0.599
	Weight			0.253	0.064	0.507	0.090
	Limb Length			-0.182	0.033	-0.411	0.227
	Physical Activity Score			0.133	0.018	0.130	0.379
Model 3		0.000	0.014				
	Sex			0.145	0.021	0.142	0.310
	Maturation			0.017	0.000	0.027	0.907
	Weight			0.131	0.017	0.291	0.360
	Limb Length			-0.111	0.012	-0.256	0.437
	Grip Strength (Mean)			0.125	0.016	0.177	0.383
Model 4		0.059	0.057				
	Sex			0.156	0.024	0.152	0.284
	Maturation			-0.149	0.022	-0.241	0.306
	Weight			0.034	0.001	0.077	0.815
	Limb Length			0.016	0.000	0.036	0.912
	Max Push-up Peak Force			0.251	0.063	0.358	0.082
Model 5		-0.013	0.002				
	Sex			0.147	0.022	0.158	0.304
	Maturation			0.040	0.002	0.064	0.783
	Weight			0.183	0.033	0.383	0.199
	Limb Length			-0.108	0.012	-0.249	0.452
	Standard Push-Up Test #			-0.043	0.002	-0.045	0.767

Appendix F

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.166					
	Sex			0.115	0.013	0.102	0.437
	Maturation			0.069	0.005	0.099	0.639
	Weight			0.317	0.100	0.613	0.028
	Limb Length			-0.124	0.015	-0.257	0.401
Model 1		0.206	0.053				
	Sex			0.198	0.039	0.182	0.181
	Maturation			0.062	0.004	0.085	0.680
	Weight			0.403	0.162	1.004	0.005
	Limb Length			-0.158	0.025	-0.320	0.289
	Muscle Area			-0.263	0.069	-0.410	0.074
Model 2		0.167	0.004				
	Sex			0.006	0.000	0.005	0.970
	Maturation			0.044	0.002	0.061	0.770
	Weight			0.332	0.110	0.663	0.024
	Limb Length			-0.108	0.012	-0.224	0.475
	Physical Activity Score			0.074	0.005	0.066	0.627
Model 3		0.157	0.002				
	Sex			0.064	0.004	0.057	0.655
	Maturation			0.006	0.000	0.009	0.967
	Weight			0.292	0.085	0.617	0.038
	Limb Length			-0.107	0.011	-0.227	0.454
	Grip Strength (Mean)			0.045	0.002	0.058	0.753
Model 4		0.145	0.003				
	Sex			0.088	0.008	0.081	0.549
	Maturation			-0.092	0.008	-0.140	0.530
	Weight			0.256	0.066	0.569	0.075
	Limb Length			-0.045	0.002	-0.097	0.758
	Max Push-up Peak Force			0.064	0.004	0.085	0.660
Model 5		0.158	0.000				
	Sex			0.062	0.004	0.061	0.663
	Maturation			-0.002	0.000	-0.002	0.991
	Weight			0.323	0.104	0.641	0.021
	Limb Length			-0.093	0.009	-0.195	0.518
	Standard Push-Up Test #			-0.008	0.000	-0.007	0.957

Distal Radius: Cortical Density

Appendix F

Distal Radius: Trabecular Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		-0.056					
	Sex			0.166	0.028	0.167	0.259
	Maturation			0.012	0.000	0.019	0.937
	Weight			-0.030	0.001	-0.062	0.839
	Limb Length			0.011	0.000	0.024	0.943
Model 1		-0.073	0.006				
	Sex			0.133	0.018	0.141	0.371
	Maturation			0.014	0.000	0.023	0.923
	Weight			-0.071	0.005	-0.189	0.634
	Limb Length			0.019	0.000	0.045	0.898
	Muscle Area			0.076	0.006	0.134	0.611
Model 2		-0.007	0.032				
	Sex			0.199	0.040	0.202	0.184
	Maturation			0.054	0.003	0.081	0.724
	Weight			0.083	0.007	0.165	0.583
	Limb Length			-0.109	0.012	-0.249	0.470
	Physical Activity Score			0.185	0.034	0.185	0.220
Model 3		-0.035	0.019				
	Sex			0.203	0.041	0.204	0.152
	Maturation			0.011	0.000	0.018	0.938
	Weight			-0.036	0.001	-0.081	0.800
	Limb Length			-0.029	0.001	-0.067	0.842
	Grip Strength (Mean)			0.140	0.020	0.202	0.327
Model 4		0.021	0.053				
	Sex			0.195	0.038	0.195	0.179
	Maturation			-0.107	0.011	-0.175	0.465
	Weight			-0.122	0.015	-0.281	0.405
	Limb Length			0.082	0.007	0.189	0.576
	Max Push-up Peak Force			0.239	0.057	0.346	0.099
Model 5		-0.057	0.002				
	Sex			0.193	0.037	0.213	0.175
	Maturation			0.052	0.003	0.086	0.715
	Weight			0.014	0.000	0.029	0.924
	Limb Length			-0.037	0.001	-0.087	0.795
	Standard Push-Up Test #			-0.043	0.002	-0.046	0.763

Appendix F

Distal Radius: Cortical Thickness

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.234					
	Sex			0.174	0.030	0.149	0.237
	Maturation			0.142	0.020	0.195	0.337
	Weight			0.348	0.121	0.652	0.015
	Limb Length			-0.166	0.028	-0.333	0.259
Model 1		0.233	0.015				
	Sex			0.211	0.045	0.211	0.154
	Maturation			0.138	0.019	0.138	0.355
	Weight			0.358	0.128	0.358	0.014
	Limb Length			-0.183	0.033	-0.183	0.219
	Muscle Area			-0.144	0.021	-0.144	0.335
Model 2		0.244	0.003				
	Sex			0.077	0.006	0.066	0.611
	Maturation			0.146	0.021	0.194	0.334
	Weight			0.375	0.141	0.692	0.010
	Limb Length			-0.171	0.029	-0.341	0.255
	Physical Activity Score			0.063	0.004	0.054	0.679
Model 3		0.222	0.019				
	Sex			0.114	0.013	0.097	0.427
	Maturation			0.043	0.002	0.062	0.765
	Weight			0.270	0.073	0.545	0.055
	Limb Length			-0.132	0.017	-0.269	0.355
	Grip Strength (Mean)			0.160	0.026	0.201	0.262
Model 4		0.194	0.009				
	Sex			0.139	0.019	0.125	0.340
	Maturation			-0.073	0.005	-0.108	0.618
	Weight			0.249	0.062	0.536	0.084
	Limb Length			-0.047	0.002	-0.099	0.746
	Max Push-up Peak Force			0.111	0.012	0.142	0.449
Model 5		0.202	0.000				
	Sex			0.104	0.011	0.099	0.467
	Maturation			0.054	0.003	0.077	0.707
	Weight			0.332	0.110	0.643	0.017
	Limb Length			-0.111	0.012	-0.229	0.436
	Standard Push-Up Test #			0.002	0.000	0.002	0.988

Appendix F

Distal Radius: Trabecular Thickness							
	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		-0.062					
	Sex			-0.061	0.004	-0.061	0.679
	Maturation			0.063	0.004	0.101	0.670
	Weight			-0.062	0.004	-0.128	0.676
	Limb Length			0.062	0.004	0.145	0.675
Model 1		-0.084	0.001				
	Sex			-0.046	0.002	-0.048	0.760
	Maturation			0.062	0.004	0.099	0.680
	Weight			-0.025	0.001	-0.066	0.869
	Limb Length			0.057	0.003	0.135	0.701
	Muscle Area			-0.037	0.001	-0.065	0.804
Model 2		-0.073	0.007				
	Sex			-0.060	0.004	-0.061	0.694
	Maturation			0.101	0.010	0.159	0.504
	Weight			0.031	0.001	0.062	0.840
	Limb Length			-0.024	0.001	-0.056	0.875
	Physical Activity Score			0.085	0.007	0.087	0.573
Model 3		-0.042	0.015				
	Sex			-0.040	0.002	-0.039	0.782
	Maturation			0.071	0.005	0.119	0.619
	Weight			-0.057	0.003	-0.129	0.690
	Limb Length			0.029	0.001	0.069	0.838
	Grip Strength (Mean)			0.126	0.016	0.182	0.378
Model 4		-0.078	0.008				
	Sex			-0.021	0.000	-0.021	0.888
	Maturation			0.007	0.000	0.011	0.963
	Weight			-0.064	0.004	-0.155	0.660
	Limb Length			0.075	0.006	0.181	0.609
	Max Push-up Peak Force			0.092	0.008	0.137	0.529
Model 5		-0.060	0.000				
	Sex			-0.040	0.002	-0.043	0.782
	Maturation			0.102	0.010	0.169	0.477
	Weight			-0.015	0.000	-0.031	0.918
	Limb Length			0.025	0.001	0.060	0.860
	Standard Push-Up Test #			0.019	0.000	0.021	0.893

Appendix F

Distal Radius: Trabecular Number

	Independent Variables	Overall R2	R2 Change	partial r	Partial R2	Beta	p-value
Base		0.119					
	Sex			0.399	0.159	0.394	0.005
	Maturation			-0.095	0.009	-0.140	0.519
	Weight			0.073	0.005	0.137	0.624
	Limb Length			-0.079	0.006	-0.168	0.593
Model 1		0.126	0.024				
	Sex			0.339	0.115	0.341	0.020
	Maturation			-0.090	0.008	-0.130	0.546
	Weight			-0.052	0.003	-0.125	0.727
	Limb Length			-0.060	0.004	-0.126	0.689
	Muscle Area			0.172	0.030	0.275	0.249
Model 2		0.234	0.036				
	Sex			0.455	0.207	0.442	0.001
	Maturation			-0.084	0.007	-0.112	0.579
	Weight			0.144	0.021	0.251	0.340
	Limb Length			-0.173	0.030	-0.348	0.249
	Physical Activity Score			0.223	0.050	0.196	0.137
Model 3		0.144	0.007				
	Sex			0.424	0.180	0.430	0.001
	Maturation			-0.106	0.011	-0.181	0.406
	Weight			0.037	0.001	0.086	0.769
	Limb Length			-0.090	0.008	-0.215	0.481
	Grip Strength (Mean)			0.085	0.007	0.126	0.501
Model 4		**0.226**	**0.074**				
	Sex			**0.404**	**0.163**	**0.384**	**0.004**
	Maturation			**-0.240**	**0.058**	**-0.357**	**0.097**
	Weight			**-0.101**	**0.010**	**-0.207**	**0.489**
	Limb Length			**0.036**	**0.001**	**0.074**	**0.805**
	Max Push-up Peak Force			**0.309**	**0.095**	**0.407**	**0.031**
Model 5		0.123	0.012				
	Sex			0.419	0.176	0.456	0.002
	Maturation			-0.081	0.007	-0.122	0.572
	Weight			0.082	0.007	0.157	0.569
	Limb Length			-0.113	0.013	-0.242	0.432
	Standard Push-Up Test #			-0.120	0.014	-0.118	0.401

Appendix F

Distal Radius: Trabecular Bone volume Fraction

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		-0.056					
	Sex			0.166	0.028	0.167	0.259
	Maturation			0.009	0.000	0.014	0.951
	Weight			-0.030	0.001	-0.061	0.842
	Limb Length			0.013	0.000	0.029	0.933
Model 1		-0.072	0.006				
	Sex			0.133	0.018	0.140	0.374
	Maturation			0.012	0.000	0.019	0.937
	Weight			-0.072	0.005	-0.191	0.630
	Limb Length			0.021	0.000	0.050	0.886
	Muscle Area			0.078	0.006	0.137	0.602
Model 2		-0.008	0.032				
	Sex			0.198	0.039	0.200	0.187
	Maturation			0.050	0.003	0.076	0.741
	Weight			0.083	0.007	0.166	0.581
	Limb Length			-0.107	0.011	-0.243	0.481
	Physical Activity Score			0.185	0.034	0.185	0.219
Model 3		-0.035	0.019				
	Sex			0.203	0.041	0.204	0.153
	Maturation			0.009	0.000	0.016	0.948
	Weight			-0.035	0.001	-0.079	0.806
	Limb Length			-0.027	0.001	-0.064	0.848
	Grip Strength (Mean)			0.140	0.020	0.202	0.327
Model 4		0.021	0.054				
	Sex			0.195	0.038	0.194	0.180
	Maturation			-0.109	0.012	-0.178	0.458
	Weight			-0.121	0.015	-0.279	0.409
	Limb Length			0.083	0.007	0.192	0.569
	Max Push-up Peak Force			0.239	0.057	0.347	0.098
Model 5		-0.057	0.002				
	Sex			0.193	0.037	0.213	0.175
	Maturation			0.051	0.003	0.083	0.752
	Weight			0.015	0.000	0.031	0.918
	Limb Length			-0.036	0.001	-0.084	0.802
	Standard Push-Up Test #			-0.044	0.002	-0.047	0.761

Appendix F

Distal Radius: BSIc							
	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.114					
	Sex			0.061	0.004	0.058	0.617
	Maturation			0.168	0.028	0.258	0.168
	Weight			0.226	0.051	0.426	0.062
	Limb Length			-0.141	0.020	-0.290	0.249
Model 1		**0.234**	**0.124**				
	Sex			**-0.054**	**0.003**	**-0.049**	**0.661**
	Maturation			**0.156**	**0.024**	**0.222**	**0.203**
	Weight			**-0.079**	**0.006**	**-0.175**	**0.524**
	Limb Length			**-0.076**	**0.006**	**-0.146**	**0.537**
	Muscle Area			**0.385**	**0.148**	**0.630**	**0.001**
Model 2		**0.188**	**0.053**				
	Sex			**0.021**	**0.000**	**0.019**	**0.863**
	Maturation			**0.205**	**0.042**	**0.298**	**0.094**
	Weight			**0.277**	**0.077**	**0.502**	**0.022**
	Limb Length			**-0.207**	**0.043**	**-0.415**	**0.091**
	Physical Activity Score			**0.257**	**0.066**	**0.236**	**0.034**
Model 3		0.147	0.011				
	Sex			0.037	0.001	0.034	0.753
	Maturation			0.144	0.021	0.227	0.220
	Weight			0.197	0.039	0.406	0.092
	Limb Length			-0.160	0.026	-0.330	0.174
	Grip Strength (Mean)			0.116	0.013	0.151	0.327
Model 4		0.155	0.002				
	Sex			0.069	0.005	0.066	0.563
	Maturation			0.107	0.011	0.175	0.370
	Weight			0.253	0.064	0.558	0.032
	Limb Length			-0.153	0.023	-0.326	0.201
	Max Push-up Peak Force			-0.049	0.002	-0.069	0.683
Model 5		0.140	0.005				
	Sex			0.019	0.000	0.018	0.870
	Maturation			0.143	0.020	0.226	0.223
	Weight			0.253	0.064	0.486	0.030
	Limb Length			-0.141	0.020	-0.295	0.231
	Standard Push-Up Test #			0.078	0.006	0.074	0.507

Appendix F

Radius Shaft: Total Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
		0.165					
Base	Sex			0.103	0.011	0.097	0.401
	Maturation			0.067	0.004	0.101	0.587
	Weight			0.302	0.091	0.579	0.012
	Limb Length			-0.161	0.026	-0.332	0.187
Model 1		**0.347**	**0.182**				
	Sex			**-0.037**	**0.001**	**-0.032**	**0.763**
	Maturation			**0.043**	**0.002**	**0.058**	**0.728**
	Weight			**-0.069**	**0.005**	**-0.148**	**0.573**
	Limb Length			**-0.086**	**0.007**	**-0.159**	**0.485**
	Muscle Area			**0.467**	**0.218**	**0.763**	**0.000**
Model 2		0.093	0.028				
	Sex			0.085	0.007	0.082	0.509
	Maturation			0.055	0.003	0.082	0.672
	Weight			0.231	0.053	0.435	0.071
	Limb Length			-0.103	0.011	-0.213	0.427
	Physical Activity Score			0.181	0.033	0.171	0.160
Model 3		**0.185**	**0.078**				
	Sex			**0.074**	**0.005**	**0.066**	**0.554**
	Maturation			**-0.027**	**0.001**	**-0.041**	**0.829**
	Weight			**0.169**	**0.029**	**0.327**	**0.171**
	Limb Length			**-0.138**	**0.019**	**-0.273**	**0.264**
	Grip Strength (Mean)			**0.306**	**0.094**	**0.422**	**0.012**
Model 4		0.133	0.005				
	Sex			0.092	0.008	0.087	0.467
	Maturation			0.129	0.017	0.198	0.308
	Weight			0.307	0.094	0.660	0.013
	Limb Length			-0.184	0.034	-0.380	0.142
	Max Push-up Peak Force			-0.081	0.007	-0.110	0.522
Model 5		0.201	0.027				
	Sex			0.035	0.001	0.033	0.782
	Maturation			0.021	0.000	0.032	0.863
	Weight			0.305	0.093	0.568	0.012
	Limb Length			-0.116	0.013	-0.236	0.351
	Standard Push-Up Test #			0.179	0.032	0.172	0.146

Appendix F

Radius Shaft: Cortical Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.331					
	Sex			0.019	0.000	0.015	0.879
	Maturation			0.176	0.031	0.236	0.147
	Weight			0.325	0.106	0.548	0.006
	Limb Length			-0.085	0.007	-0.151	0.487
Model 1		**0.428**	**0.100**				
	Sex			**-0.102**	**0.010**	**-0.080**	**0.406**
	Maturation			**0.166**	**0.028**	**0.204**	**0.176**
	Weight			**0.005**	**0.000**	**0.009**	**0.969**
	Limb Length			**-0.014**	**0.000**	**-0.023**	**0.911**
	Muscle Area			**0.398**	**0.158**	**0.565**	**0.001**
Model 2		0.310	0.022				
	Sex			0.006	0.000	0.005	0.963
	Maturation			0.164	0.027	0.216	0.204
	Weight			0.257	0.066	0.425	0.044
	Limb Length			-0.020	0.000	-0.036	0.877
	Physical Activity Score			0.181	0.033	0.150	0.158
Model 3		**0.393**	**0.068**				
	Sex			**-0.020**	**0.000**	**-0.016**	**0.869**
	Maturation			**0.081**	**0.007**	**0.106**	**0.513**
	Weight			**0.187**	**0.035**	**0.314**	**0.129**
	Limb Length			**-0.058**	**0.003**	**-0.097**	**0.643**
	Grip Strength (Mean)			**0.328**	**0.108**	**0.393**	**0.007**
Model 4		0.327	0.002				
	Sex			0.016	0.000	0.013	0.899
	Maturation			0.192	0.037	0.263	0.126
	Weight			0.308	0.095	0.582	0.013
	Limb Length			-0.089	0.008	-0.159	0.482
	Max Push-up Peak Force			-0.049	0.002	-0.059	0.698
Model 5		0.332	0.003				
	Sex			-0.015	0.000	-0.013	0.904
	Maturation			0.155	0.024	0.209	0.211
	Weight			0.327	0.107	0.542	0.007
	Limb Length			-0.062	0.004	-0.111	0.618
	Standard Push-Up Test #			0.071	0.005	0.059	0.567

Appendix F

Radius Shaft: Cortical Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.129					
	Sex			-0.052	0.003	-0.049	0.699
	Maturation			0.178	0.032	0.272	0.144
	Weight			0.017	0.000	0.031	0.890
	Limb Length			0.070	0.005	0.143	0.566
Model 1		**0.226**	**0.103**				
	Sex			**0.053**	**0.003**	**0.048**	**0.668**
	Maturation			**0.211**	**0.045**	**0.305**	**0.084**
	Weight			**0.250**	**0.063**	**0.577**	**0.040**
	Limb Length			**0.006**	**0.000**	**0.012**	**0.960**
	Muscle Area			**-0.353**	**0.125**	**-0.573**	**0.003**
Model 2		0.135	0.031				
	Sex			-0.033	0.001	-0.031	0.796
	Maturation			0.157	0.025	0.231	0.224
	Weight			0.084	0.007	0.150	0.518
	Limb Length			0.041	0.002	0.082	0.755
	Physical Activity Score			-0.194	0.038	-0.180	0.130
Model 3		**0.185**	**0.066**				
	Sex			**-0.022**	**0.000**	**-0.020**	**0.859**
	Maturation			**0.257**	**0.066**	**0.401**	**0.036**
	Weight			**0.136**	**0.018**	**0.262**	**0.273**
	Limb Length			**0.045**	**0.002**	**0.088**	**0.717**
	Grip Strength (Mean)			**-0.284**	**0.081**	**-0.388**	**0.020**
Model 4		0.070	0.004				
	Sex			-0.035	0.001	-0.035	0.780
	Maturation			0.100	0.010	0.158	0.430
	Weight			-0.030	0.001	-0.063	0.815
	Limb Length			0.106	0.011	0.224	0.401
	Max Push-up Peak Force			0.071	0.005	0.100	0.575
Model 5		0.102	0.000				
	Sex			-0.030	0.001	-0.030	0.807
	Maturation			0.182	0.033	0.286	0.141
	Weight			0.015	0.000	0.026	0.907
	Limb Length			0.057	0.003	0.119	0.645
	Standard Push-Up Test #			-0.022	0.000	-0.021	0.862

Appendix F

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Radius Shaft: SSIp							
Base		0.495					
	Sex			0.145	0.021	0.103	0.236
	Maturation			0.227	0.052	0.266	0.061
	Weight			0.473	0.224	0.743	0.000
	Limb Length			-0.180	0.032	-0.282	0.140
Model 1		**0.562**	**0.069**				
	Sex			**0.035**	**0.001**	**0.024**	**0.776**
	Maturation			**0.220**	**0.048**	**0.240**	**0.071**
	Weight			**0.173**	**0.030**	**0.295**	**0.158**
	Limb Length			**-0.120**	**0.014**	**-0.175**	**0.332**
	Muscle Area			**0.381**	**0.145**	**0.470**	**0.001**
Model 2		0.477	0.005				
	Sex			0.115	0.013	0.084	0.374
	Maturation			0.147	0.022	0.168	0.254
	Weight			0.452	0.204	0.705	0.000
	Limb Length			-0.102	0.010	-0.161	0.429
	Physical Activity Score			0.098	0.010	0.069	0.451
Model 3		**0.516**	**0.028**				
	Sex			**0.125**	**0.016**	**0.087**	**0.315**
	Maturation			**0.153**	**0.023**	**0.179**	**0.217**
	Weight			**0.373**	**0.139**	**0.591**	**0.002**
	Limb Length			**-0.161**	**0.026**	**-0.245**	**0.193**
	Grip Strength (Mean)			**0.244**	**0.060**	**0.255**	**0.046**
Model 4		0.512	0.006				
	Sex			0.155	0.024	0.111	0.218
	Maturation			0.269	0.072	0.320	0.030
	Weight			0.468	0.219	0.812	0.000
	Limb Length			-0.195	0.038	-0.303	0.119
	Max Push-up Peak Force			-0.110	0.012	-0.112	0.385
Model 5		0.511	0.015				
	Sex			0.078	0.006	0.057	0.528
	Maturation			0.184	0.034	0.214	0.135
	Weight			0.478	0.228	0.729	0.000
	Limb Length			-0.136	0.018	-0.209	0.272
	Standard Push-Up Test #			0.177	0.031	0.128	0.153

Appendix F

Distal Tibia: Total Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.459					
	Sex			0.429	0.184	0.340	0.003
	Maturation			0.260	0.068	0.313	0.081
	Weight			0.235	0.055	0.283	0.115
	Limb Length			0.032	0.001	0.045	0.834
Model 1		0.511	0.022				
	Sex			0.441	0.194	0.339	0.001
	Maturation			0.280	0.078	0.353	0.047
	Weight			-0.080	0.006	-0.203	0.577
	Limb Length			0.115	0.013	0.172	0.421
	Muscle Area			0.217	0.047	0.418	0.126
Model 2		0.484	0.001				
	Sex			0.408	0.166	0.314	0.003
	Maturation			0.229	0.052	0.291	0.109
	Weight			0.142	0.020	0.391	0.324
	Limb Length			0.047	0.002	0.070	0.744
	CMJMax Force (N)			-0.042	0.002	-0.093	0.770
Model 3		0.503	0.018				
	Sex			0.376	0.141	0.282	0.007
	Maturation			0.169	0.029	0.217	0.240
	Weight			0.082	0.007	0.121	0.571
	Limb Length			0.038	0.001	0.054	0.795
	CMJ Impulse (Ns)			0.196	0.038	0.296	0.173
Model 4		0.490	0.007				
	Sex			0.376	0.141	0.288	0.007
	Maturation			0.206	0.042	0.262	0.152
	Weight			0.120	0.014	0.182	0.406
	Limb Length			0.053	0.003	0.077	0.713
	CMJ Peak Power			0.119	0.014	0.165	0.409
Model 5		0.520	0.033				
	Sex			0.327	0.107	0.245	0.020
	Maturation			0.124	0.015	0.160	0.390
	Weight			0.286	0.082	0.363	0.044
	Limb Length			0.109	0.012	0.157	0.453
	LJ Mean			0.266	0.071	0.210	0.062

Appendix F

Distal Tibia: Total Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.492	0.008				
	Sex			0.424	0.180	0.340	0.002
	Maturation			0.216	0.047	0.271	0.132
	Weight			0.059	0.003	0.108	0.685
	Limb Length			0.056	0.003	0.081	0.700
	LJ Vert Force (N)			0.131	0.017	0.219	0.366
Model 7		0.500	0.016				
	Sex			0.432	0.187	0.332	0.002
	Maturation			0.239	0.057	0.295	0.094
	Weight			0.271	0.073	0.357	0.057
	Limb Length			0.062	0.004	0.089	0.670
	LJ Vert Impulse (Ns)			-0.182	0.033	-0.147	0.205
Model 8		0.492	0.008				
	Sex			0.406	0.165	0.306	0.003
	Maturation			0.228	0.052	0.284	0.111
	Weight			0.129	0.017	0.187	0.371
	Limb Length			0.067	0.004	0.097	0.646
	LJ Peak Vert Power (W)			0.131	0.017	0.135	0.363
Model 9		0.497	0.012				
	Sex			0.400	0.160	0.300	0.004
	Maturation			0.194	0.038	0.246	0.177
	Weight			0.121	0.015	0.171	0.404
	Limb Length			0.062	0.004	0.089	0.670
	LJ Max Horiz. Force			0.163	0.027	0.191	0.258
Model 10		0.485	0.001				
	Sex			0.408	0.166	0.310	0.003
	Maturation			0.162	0.026	0.291	0.108
	Weight			0.144	0.021	0.269	0.150
	Limb Length			0.037	0.001	0.079	0.709
	LJ Horiz. Impulse (Ns)			0.038	0.001	0.048	0.698
Model 11		0.497	0.013				
	Sex			0.394	0.155	0.295	0.005
	Maturation			0.185	0.034	0.237	0.199
	Weight			0.201	0.040	0.253	0.162
	Limb Length			0.062	0.004	0.089	0.670
	LJ Peak Horiz Power (W)			0.165	0.027	0.144	0.251
Model 12		0.472	0.024				
	Sex			0.379	0.144	0.296	0.010
	Maturation			0.268	0.072	0.316	0.075
	Weight			0.186	0.035	0.223	0.220
	Limb Length			0.076	0.006	0.107	0.622
	PA Score			0.218	0.048	0.164	0.150

Appendix F

Distal Tibia: Cortical Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.504					
	Sex			0.313	0.098	0.225	0.034
	Maturation			-0.017	0.000	-0.019	0.908
	Weight			0.508	0.258	0.659	0.000
	Limb Length			0.027	0.001	0.037	0.859
Model 1		0.504	0.006				
	Sex			0.261	0.068	0.188	0.064
	Maturation			-0.074	0.005	-0.090	0.608
	Weight			0.343	0.118	0.932	0.014
	Limb Length			0.017	0.000	0.025	0.907
	Muscle Area			-0.115	0.013	-0.219	0.422
Model 2		0.517	0.024				
	Sex			0.263	0.069	0.185	0.065
	Maturation			-0.004	0.000	-0.004	0.980
	Weight			0.046	0.002	0.122	0.749
	Limb Length			0.076	0.006	0.110	0.598
	CMJMax Force (N)			0.227	0.052	0.497	0.112
Model 3		0.491	0.001				
	Sex			0.282	0.080	0.207	0.047
	Maturation			-0.056	0.003	-0.071	0.700
	Weight			0.396	0.157	0.640	0.004
	Limb Length			0.036	0.001	0.053	0.801
	CMJ Impulse (Ns)			0.034	0.001	0.050	0.817
Model 4		0.497	0.006				
	Sex			0.262	0.069	0.192	0.066
	Maturation			-0.075	0.006	-0.094	0.603
	Weight			0.356	0.127	0.569	0.011
	Limb Length			0.038	0.001	0.055	0.792
	CMJ Peak Power			0.113	0.013	0.155	0.435
Model 5		0.491	0.000				
	Sex			0.280	0.078	0.213	0.049
	Maturation			-0.041	0.002	-0.054	0.777
	Weight			0.470	0.221	0.667	0.001
	Limb Length			0.038	0.001	0.056	0.795
	LJ Mean			-0.006	0.000	-0.004	0.969

Appendix F

Distal Tibia: Cortical Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.515	0.022				
	Sex			0.348	0.121	0.264	0.013
	Maturation			-0.089	0.008	-0.107	0.538
	Weight			0.201	0.040	0.368	0.161
	Limb Length			0.042	0.002	0.059	0.772
	LJ Vert Force (N)			0.219	0.048	0.366	0.126
Model 7		0.491	0.001				
	Sex			0.284	0.081	0.207	0.046
	Maturation			-0.046	0.002	-0.056	0.749
	Weight			0.457	0.209	0.656	0.001
	Limb Length			0.038	0.001	0.056	0.791
	LJ Vert Impulse (Ns)			0.034	0.001	0.027	0.817
Model 8		0.494	0.003				
	Sex			0.291	0.085	0.210	0.040
	Maturation			-0.055	0.003	-0.067	0.703
	Weight			0.392	0.154	0.611	0.005
	Limb Length			0.046	0.002	0.067	0.750
	LJ Peak Vert Power (W)			0.075	0.006	0.076	0.604
Model 9		0.491	0.000				
	Sex			0.291	0.085	0.210	0.040
	Maturation			-0.051	0.003	-0.064	0.724
	Weight			0.419	0.176	0.653	0.002
	Limb Length			0.040	0.002	0.059	0.781
	LJ Max Horiz. Force			0.021	0.000	0.025	0.884
Model 10		0.492	0.001				
	Sex			0.295	0.087	0.212	0.038
	Maturation			-0.055	0.003	-0.067	0.704
	Weight			0.457	0.209	0.650	0.001
	Limb Length			0.039	0.002	0.057	0.788
	LJ Horiz. Impulse (Ns)			0.054	0.003	0.045	0.712
Model 11		0.491	0.000				
	Sex			0.292	0.085	0.212	0.039
	Maturation			-0.043	0.002	-0.054	0.769
	Weight			0.476	0.227	0.670	0.000
	Limb Length			0.039	0.002	0.057	0.787
	LJ Peak Horiz Power (W)			-0.008	0.000	-0.007	0.957
Model 12		0.494	0.001				
	Sex			0.315	0.099	0.235	0.035
	Maturation			-0.018	0.000	-0.020	0.906
	Weight			0.506	0.256	0.674	0.000
	Limb Length			0.016	0.000	0.022	0.917
	PA Score			-0.054	0.003	-0.039	0.726

Appendix F

Distal Tibia: Trabecular Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.350					
	Sex			0.378	0.143	0.320	0.010
	Maturation			0.251	0.063	0.331	0.092
	Weight			0.149	0.022	0.193	0.322
	Limb Length			0.023	0.001	0.036	0.877
Model 1		0.412	0.029				
	Sex			0.397	0.158	0.328	0.004
	Maturation			0.280	0.078	0.388	0.047
	Weight			-0.130	0.017	-0.364	0.363
	Limb Length			0.106	0.011	0.172	0.460
	Muscle Area			0.226	0.051	0.479	0.110
Model 2		0.380	0.004				
	Sex			0.365	0.133	0.302	0.009
	Maturation			0.221	0.049	0.307	0.124
	Weight			0.137	0.019	0.412	0.342
	Limb Length			0.031	0.001	0.049	0.833
	CMJMax Force (N)			-0.080	0.006	-0.193	0.581
Model 3		0.398	0.020				
	Sex			0.325	0.106	0.263	0.021
	Maturation			0.170	0.029	0.239	0.239
	Weight			0.015	0.000	0.025	0.915
	Limb Length			0.027	0.001	0.043	0.852
	CMJ Impulse (Ns)			0.187	0.035	0.309	0.195
Model 4		0.383	0.006				
	Sex			0.329	0.108	0.272	0.020
	Maturation			0.207	0.043	0.291	0.149
	Weight			0.061	0.004	0.102	0.672
	Limb Length			0.042	0.002	0.067	0.771
	CMJ Peak Power			0.100	0.010	0.153	0.488
Model 5		0.417	0.037				
	Sex			0.276	0.076	0.224	0.052
	Maturation			0.126	0.016	0.178	0.384
	Weight			0.204	0.042	0.279	0.156
	Limb Length			0.095	0.009	0.151	0.512
	LJ Mean			0.256	0.066	0.221	0.073

Appendix F

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.382	0.005				
	Sex			0.367	0.135	0.317	0.009
	Maturation			0.219	0.048	0.303	0.127
	Weight			0.028	0.001	0.056	0.849
	Limb Length			0.044	0.002	0.071	0.761
	LJ Vert Force (N)			0.095	0.009	0.175	0.513
Model 7		0.398	0.019				
	Sex			0.385	0.148	0.317	0.006
	Maturation			0.237	0.056	0.320	0.098
	Weight			0.195	0.038	0.276	0.175
	Limb Length			0.050	0.003	0.080	0.728
	LJ Vert Impulse (Ns)			-0.184	0.034	-0.163	0.201
Model 8		0.385	0.008				
	Sex			0.356	0.127	0.288	0.011
	Maturation			0.227	0.052	0.310	0.114
	Weight			0.063	0.004	0.099	0.665
	Limb Length			0.054	0.003	0.087	0.709
	LJ Peak Vert Power (W)			0.119	0.014	0.134	0.410
Model 9		0.391	0.013				
	Sex			0.350	0.123	0.283	0.013
	Maturation			0.194	0.038	0.271	0.176
	Weight			0.052	0.003	0.080	0.720
	Limb Length			0.050	0.003	0.079	0.731
	LJ Max Horiz. Force			0.151	0.023	0.194	0.295
Model 10		0.377	0.001				
	Sex			0.358	0.128	0.292	0.011
	Maturation			0.230	0.053	0.319	0.108
	Weight			0.130	0.017	0.185	0.365
	Limb Length			0.043	0.002	0.069	0.767
	LJ Horiz. Impulse (Ns)			0.040	0.002	0.037	0.785
Model 11		0.392	0.014				
	Sex			0.343	0.118	0.277	0.015
	Maturation			0.184	0.034	0.260	0.200
	Weight			0.119	0.014	0.163	0.409
	Limb Length			0.050	0.003	0.079	0.731
	LJ Peak Horiz Power (W)			0.156	0.024	0.149	0.278
Model 12		0.364	0.026				
	Sex			0.326	0.106	0.274	0.029
	Maturation			0.259	0.067	0.335	0.086
	Weight			0.100	0.010	0.130	0.513
	Limb Length			0.065	0.004	0.102	0.670
	PA Score			0.210	0.044	0.173	0.167

Distal Tibia: Trabecular Area

Appendix F

	Distal Tibia: Total Density						
	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.106					
	Sex			0.613	0.376	0.307	0.024
	Maturation			-0.107	0.011	-0.174	0.453
	Weight			0.279	0.078	0.475	0.047
	Limb Length			-0.111	0.012	-0.216	0.439
Model 1		0.105	0.015		0.000		
	Sex			0.283	0.080	0.275	0.045
	Maturation			-0.136	0.018	-0.226	0.341
	Weight			0.253	0.064	0.895	0.073
	Limb Length			-0.138	0.019	-0.278	0.335
	Muscle Area			-0.136	0.018	-0.350	0.340
					0.000		
Model 2		0.103	0.014		0.000		
	Sex			0.295	0.087	0.286	0.037
	Maturation			-0.082	0.007	-0.133	0.573
	Weight			0.014	0.000	0.051	0.922
	Limb Length			-0.090	0.008	-0.176	0.535
	CMJMax Force (N)			0.132	0.017	0.385	0.362
					0.000		
Model 3		0.097	0.009		0.000		
	Sex			0.294	0.086	0.288	0.038
	Maturation			-0.135	0.018	-0.233	0.349
	Weight			0.179	0.032	0.359	0.215
	Limb Length			-0.120	0.014	-0.234	0.407
	CMJ Impulse (Ns)			0.102	0.010	0.205	0.479
					0.000		
Model 4		0.102	0.013		0.000		
	Sex			0.282	0.080	0.277	0.047
	Maturation			-0.137	0.019	-0.229	0.343
	Weight			0.161	0.026	0.326	0.264
	Limb Length			-0.113	0.013	-0.219	0.433
	CMJ Peak Power			0.127	0.016	0.232	0.381
Model 5		0.181	0.008		0.000		
	Sex			0.273	0.075	0.276	0.055
	Maturation			-0.137	0.019	-0.243	0.342
	Weight			0.293	0.086	0.511	0.039
	Limb Length			-0.090	0.008	-0.179	0.532
	LJ Mean			0.097	0.009	0.102	0.502

Appendix F

Distal Tibia: Total Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.091	0.004				
	Sex			0.320	0.102	0.328	0.024
	Maturation			-0.118	0.014	-0.195	0.414
	Weight			0.142	0.020	0.351	0.326
	Limb Length			-0.111	0.012	-0.215	0.445
	LJ Vert Force (N)			0.068	0.005	0.151	0.641
Model 7		0.090	0.003				
	Sex			0.303	0.092	0.298	0.033
	Maturation			-0.106	0.011	-0.172	0.465
	Weight			0.253	0.064	0.447	0.076
	Limb Length			-0.113	0.013	-0.220	0.436
	LJ Vert Impulse (Ns)			0.055	0.003	0.060	0.702
Model 8		0.100	0.011				
	Sex			0.313	0.098	0.303	0.027
	Maturation			-0.120	0.014	-0.195	0.407
	Weight			0.183	0.033	0.355	0.204
	Limb Length			-0.101	0.010	-0.196	0.487
	LJ Peak Vert Power (W)			0.118	0.014	0.160	0.416
Model 9		0.089	0.002				
	Sex			0.318	0.101	0.310	0.024
	Maturation			-0.092	0.008	-0.155	0.525
	Weight			0.263	0.069	0.517	0.064
	Limb Length			-0.112	0.013	-0.219	0.437
	LJ Max Horiz. Force			-0.044	0.002	-0.068	0.763
Model 10		0.089	0.002				
	Sex			0.315	0.099	0.306	0.026
	Maturation			-0.099	0.010	-0.162	0.495
	Weight			0.281	0.079	0.497	0.048
	Limb Length			-0.110	0.012	-0.215	0.446
	LJ Horiz. Impulse (Ns)			-0.048	0.002	-0.055	0.739
Model 11		0.088	0.001				
	Sex			0.316	0.100	0.310	0.025
	Maturation			-0.095	0.009	-0.161	0.513
	Weight			0.279	0.078	0.482	0.050
	Limb Length			-0.112	0.013	-0.218	0.440
	LJ Peak Horiz Power (W)			-0.025	0.001	-0.029	0.861
Model 12		0.137	0.003				
	Sex			0.329	0.108	0.322	0.027
	Maturation			-0.176	0.031	-0.260	0.248
	Weight			0.293	0.086	0.456	0.051
	Limb Length			-0.075	0.006	-0.137	0.623
	PA Score			0.067	0.004	0.063	0.664

Appendix F

Distal Tibia: Cortical Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.251					
	Sex			0.079	0.006	0.067	0.582
	Maturation			-0.027	0.001	-0.039	0.853
	Weight			0.384	0.147	0.622	0.005
	Limb Length			-0.037	0.001	-0.065	0.797
Model 1		0.244	0.004				
	Sex			0.063	0.004	0.054	0.659
	Maturation			-0.040	0.002	-0.061	0.778
	Weight			0.254	0.065	0.827	0.072
	Limb Length			-0.055	0.003	-0.101	0.703
	Muscle Area			-0.072	0.005	-0.169	0.615
Model 2		0.247	0.011				
	Sex			0.058	0.003	0.049	0.689
	Maturation			-0.003	0.000	-0.004	0.985
	Weight			0.078	0.006	0.257	0.590
	Limb Length			-0.017	0.000	-0.031	0.906
	CMJMax Force (N)			0.124	0.015	0.332	0.391
Model 3		0.238	0.002				
	Sex			0.066	0.004	0.057	0.649
	Maturation			-0.044	0.002	-0.069	0.760
	Weight			0.295	0.087	0.562	0.037
	Limb Length			-0.042	0.002	-0.075	0.773
	CMJ Impulse (Ns)			0.058	0.003	0.106	0.689
Model 4		0.250	0.013				
	Sex			0.043	0.002	0.037	0.765
	Maturation			-0.062	0.004	-0.094	0.670
	Weight			0.251	0.063	0.473	0.079
	Limb Length			-0.039	0.002	-0.069	0.787
	CMJ Peak Power			0.138	0.019	0.232	0.340
Model 5		0.244	0.008				
	Sex			0.110	0.012	0.098	0.449
	Maturation			0.018	0.000	0.029	0.900
	Weight			0.358	0.128	0.586	0.011
	Limb Length			-0.057	0.003	-0.103	0.694
	LJ Mean			-0.106	0.011	-0.102	0.462

Appendix F

Distal Tibia: Cortical Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.253	0.016				
	Sex			0.125	0.016	0.111	0.388
	Maturation			-0.055	0.003	-0.082	0.705
	Weight			0.163	0.027	0.367	0.258
	Limb Length			-0.036	0.001	-0.064	0.802
	LJ Vert Force (N)			0.152	0.023	0.310	0.293
Model 7		0.235	0.000				
	Sex			0.079	0.006	0.068	0.588
	Maturation			-0.027	0.001	-0.039	0.854
	Weight			0.370	0.137	0.624	0.008
	Limb Length			-0.037	0.001	-0.065	0.801
	LJ Vert Impulse (Ns)			-0.005	0.000	-0.005	0.972
Model 8		0.236	0.001				
	Sex			0.077	0.006	0.066	0.593
	Maturation			-0.031	0.001	-0.045	0.833
	Weight			0.316	0.100	0.586	0.026
	Limb Length			-0.033	0.001	-0.059	0.818
	LJ Peak Vert Power (W)			0.039	0.002	0.048	0.791
Model 9		0.235	0.000				
	Sex			0.080	0.006	0.068	0.581
	Maturation			-0.021	0.000	-0.033	0.884
	Weight			0.345	0.119	0.636	0.014
	Limb Length			-0.037	0.001	-0.067	0.796
	LJ Max Horiz. Force			-0.016	0.000	-0.023	0.911
Model 10		0.237	0.001				
	Sex			0.078	0.006	0.066	0.588
	Maturation			-0.019	0.000	-0.029	0.894
	Weight			0.382	0.146	0.640	0.006
	Limb Length			-0.036	0.001	-0.065	0.802
	LJ Horiz. Impulse (Ns)			-0.044	0.002	-0.046	0.759
Model 11		0.239	0.004				
	Sex			0.087	0.008	0.074	0.547
	Maturation			-0.003	0.000	-0.005	0.983
	Weight			0.390	0.152	0.641	0.005
	Limb Length			-0.040	0.002	-0.070	0.785
	LJ Peak Horiz Power (W)			-0.073	0.005	-0.077	0.617
Model 12		0.284	0.027				
	Sex			0.145	0.021	0.123	0.343
	Maturation			0.041	0.002	0.055	0.787
	Weight			0.448	0.201	0.685	0.002
	Limb Length			-0.116	0.013	-0.193	0.447
	PA Score			-0.202	0.041	-0.176	0.183

Appendix F

Distal Tibia: Trabecular Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.105					
	Sex			0.384	0.147	0.384	0.005
	Maturation			-0.025	0.001	-0.040	0.862
	Weight			0.127	0.016	0.209	0.376
	Limb Length			-0.164	0.027	-0.322	0.251
Model 1		0.088	0.003				
	Sex			0.362	0.131	0.365	0.009
	Maturation			-0.040	0.002	-0.067	0.778
	Weight			0.114	0.013	0.396	0.427
	Limb Length			-0.167	0.028	-0.343	0.240
	Muscle Area			-0.060	0.004	-0.154	0.675
Model 2							
	Sex	0.087	0.001	0.375	0.141	0.379	0.007
	Maturation			-0.019	0.000	-0.031	0.897
	Weight			0.031	0.001	0.111	0.832
	Limb Length			-0.157	0.025	-0.313	0.275
	CMJMax Force (N)			0.030	0.001	0.089	0.835
Model 3		0.113	0.024				
	Sex			0.340	0.116	0.352	0.012
	Maturation			-0.081	0.007	-0.137	0.575
	Weight			0.008	0.000	0.016	0.956
	Limb Length			-0.180	0.032	-0.352	0.211
	CMJ Impulse (Ns)			0.171	0.029	0.342	0.236
Model 4		0.101	0.014				
	Sex			0.351	0.123	0.353	0.013
	Maturation			-0.058	0.003	-0.096	0.689
	Weight			0.028	0.001	0.056	0.848
	Limb Length			-0.167	0.028	-0.326	0.247
	CMJ Peak Power			0.130	0.017	0.239	0.369
Model 5		0.142	0.051				
	Sex			0.306	0.094	0.304	0.031
	Maturation			-0.125	0.016	-0.215	0.387
	Weight			0.182	0.033	0.302	0.205
	Limb Length			-0.118	0.014	-0.227	0.416
	LJ Mean			0.248	0.062	0.260	0.082

Appendix F

Distal Tibia: Trabecular Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.086	0.000				
	Sex			0.366	0.134	0.385	0.009
	Maturation			-0.025	0.001	-0.041	0.863
	Weight			0.082	0.007	0.203	0.570
	Limb Length			-0.164	0.027	-0.322	0.265
	LJ Vert Force (N)			0.003	0.000	0.007	0.983
Model 7		0.086	0.000				
	Sex			0.377	0.142	0.382	0.007
	Maturation			-0.025	0.001	-0.040	0.866
	Weight			0.118	0.014	0.203	0.416
	Limb Length			-0.164	0.027	-0.323	0.255
	LJ Vert Impulse (Ns)			0.012	0.000	0.013	0.936
Model 8		0.109	0.021				
	Sex			0.383	0.147	0.378	0.006
	Maturation			-0.042	0.002	-0.068	0.770
	Weight			0.024	0.001	0.045	0.869
	Limb Length			-0.151	0.023	-0.294	0.295
	LJ Peak Vert Power (W)			0.160	0.026	0.219	0.266
Model 9		0.086	0.000				
	Sex			0.383	0.147	0.384	0.006
	Maturation			-0.024	0.001	-0.040	0.870
	Weight			0.110	0.012	0.209	0.448
	Limb Length			-0.164	0.027	-0.322	0.256
	LJ Max Horiz. Force			-0.001	0.000	-0.001	0.997
Model 10		0.091	0.005				
	Sex			0.384	0.147	0.383	0.006
	Maturation			-0.013	0.000	-0.021	0.929
	Weight			0.142	0.020	0.243	0.325
	Limb Length			-0.163	0.027	-0.320	0.257
	LJ Horiz. Impulse (Ns)			-0.075	0.006	-0.085	0.604
Model 11		0.087	0.001				
	Sex			0.378	0.143	0.379	0.007
	Maturation			-0.036	0.001	-0.061	0.805
	Weight			0.118	0.014	0.197	0.414
	Limb Length			-0.162	0.026	-0.319	0.260
	LJ Peak Horiz Power (W)			0.040	0.002	0.046	0.784
Model 12		0.192	0.029				
	Sex			0.393	0.154	0.382	0.008
	Maturation			-0.148	0.022	-0.211	0.331
	Weight			0.095	0.009	0.138	0.535
	Limb Length			-0.093	0.009	-0.163	0.544
	PA Score			0.198	0.039	0.183	0.193

Appendix F

Distal Tibia: Cortical Thickness

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.310					
	Sex			0.180	0.032	0.148	0.230
	Maturation			-0.106	0.011	-0.141	0.482
	Weight			0.420	0.176	0.612	0.004
	Limb Length			0.036	0.001	0.057	0.813
Model 1		0.313	0.011				
	Sex			0.139	0.019	0.114	0.332
	Maturation			-0.153	0.023	-0.222	0.285
	Weight			0.312	0.097	0.986	0.026
	Limb Length			0.011	0.000	0.020	0.937
	Muscle Area			-0.132	0.017	-0.297	0.354
Model 2		0.319	0.023				
	Sex			0.144	0.021	0.118	0.319
	Maturation			-0.089	0.008	-0.127	0.539
	Weight			0.028	0.001	0.087	0.847
	Limb Length			0.071	0.005	0.121	0.625
	CMJMax Force (N)			0.191	0.036	0.492	0.184
Model 3		0.293	0.000				
	Sex			0.170	0.029	0.143	0.239
	Maturation			-0.120	0.014	-0.182	0.407
	Weight			0.335	0.112	0.623	0.017
	Limb Length			0.040	0.002	0.068	0.784
	CMJ Impulse (Ns)			0.006	0.000	0.010	0.969
Model 4		0.298	0.005				
	Sex			0.149	0.022	0.126	0.301
	Maturation			-0.143	0.020	-0.212	0.322
	Weight			0.292	0.085	0.540	0.039
	Limb Length			0.039	0.002	0.067	0.787
	CMJ Peak Power			0.086	0.007	0.138	0.555
Model 5		0.296	0.003				
	Sex			0.186	0.035	0.162	0.196
	Maturation			-0.089	0.008	-0.138	0.540
	Weight			0.381	0.145	0.607	0.006
	Limb Length			0.027	0.001	0.046	0.854
	LJ Mean			-0.067	0.004	-0.061	0.646

Appendix F

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.311	0.016				
	Sex			0.217	0.047	0.188	0.131
	Maturation			-0.154	0.024	-0.222	0.287
	Weight			0.172	0.030	0.372	0.233
	Limb Length			0.042	0.002	0.071	0.733
	LJ Vert Force (N)			0.159	0.025	0.313	0.270
Model 7		0.294	0.001				
	Sex			0.165	0.027	0.138	0.251
	Maturation			-0.124	0.015	-0.178	0.391
	Weight			0.377	0.142	0.613	0.007
	Limb Length			0.039	0.002	0.067	0.787
	LJ Vert Impulse (Ns)			0.035	0.001	0.033	0.809
Model 8		0.296	0.003				
	Sex			0.172	0.030	0.141	0.233
	Maturation			-0.132	0.017	-0.190	0.362
	Weight			0.319	0.102	0.568	0.024
	Limb Length			0.046	0.002	0.079	0.750
	LJ Peak Vert Power (W)			0.067	0.004	0.081	0.642
Model 9		0.295	0.002				
	Sex			0.178	0.032	0.147	0.216
	Maturation			-0.106	0.011	-0.158	0.462
	Weight			0.376	0.141	0.675	0.007
	Limb Length			0.038	0.001	0.065	0.792
	LJ Max Horiz. Force			-0.055	0.003	-0.075	0.706
Model 10		0.293	0.000				
	Sex			0.174	0.030	0.144	0.226
	Maturation			-0.126	0.016	-0.183	0.384
	Weight			0.385	0.148	0.623	0.006
	Limb Length			0.040	0.002	0.069	0.782
	LJ Horiz. Impulse (Ns)			0.015	0.000	0.015	0.917
Model 11		0.296	0.003				
	Sex			0.181	0.033	0.150	0.209
	Maturation			-0.099	0.010	-0.149	0.493
	Weight			0.405	0.164	0.646	0.004
	Limb Length			0.038	0.001	0.065	0.794
	LJ Peak Horiz Power (W)			-0.067	0.004	-0.068	0.644
Model 12		0.299	0.005				
	Sex			0.196	0.038	0.167	0.197
	Maturation			-0.108	0.012	-0.142	0.481
	Weight			0.427	0.182	0.638	0.003
	Limb Length			0.019	0.000	0.030	0.903
	PA Score			-0.084	0.007	-0.072	0.581

Distal Tibia: Cortical Thickness

Appendix F

Distal Tibia: Trabecular Thickness

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		-0.040					
	Sex			0.125	0.016	0.125	0.406
	Maturation			0.038	0.001	0.061	0.803
	Weight			-0.175	0.031	-0.289	0.244
	Limb Length			0.103	0.011	0.204	0.496
Model 1		-0.053	0.005				
	Sex			0.059	0.003	0.059	0.683
	Maturation			0.071	0.005	0.127	0.619
	Weight			-0.008	0.000	-0.031	0.954
	Limb Length			0.066	0.004	0.144	0.643
	Muscle Area			-0.070	0.005	-0.193	0.626
Model 2		-0.051	0.004				
	Sex			0.101	0.010	0.102	0.484
	Maturation			0.114	0.013	0.203	0.429
	Weight			-0.127	0.016	-0.469	0.380
	Limb Length			0.069	0.005	0.146	0.633
	CMJMax Force (N)			0.065	0.004	0.204	0.654
Model 3		-0.055	0.001				
	Sex			0.106	0.011	0.108	0.463
	Maturation			0.090	0.008	0.166	0.536
	Weight			-0.140	0.020	-0.302	0.332
	Limb Length			0.057	0.003	0.120	0.693
	CMJ Impulse (Ns)			0.025	0.001	0.055	0.861
Model 4		-0.055	0.000				
	Sex			0.113	0.013	0.116	0.436
	Maturation			0.103	0.011	0.187	0.475
	Weight			-0.118	0.014	-0.257	0.416
	Limb Length			0.060	0.004	0.125	0.680
	CMJ Peak Power			-0.012	0.000	-0.023	0.936
Model 5		-0.054	0.001				
	Sex			0.095	0.009	0.100	0.513
	Maturation			0.080	0.006	0.152	0.580
	Weight			-0.141	0.020	-0.256	0.330
	Limb Length			0.066	0.004	0.140	0.649
	LJ Mean			0.038	0.001	0.043	0.791

Appendix F

Distal Tibia: Trabecular Thickness

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		-0.055	0.000				
	Sex			0.113	0.013	0.119	0.436
	Maturation			0.099	0.010	0.176	0.494
	Weight			-0.115	0.013	-0.306	0.427
	Limb Length			0.060	0.004	0.125	0.680
	LJ Vert Force (N)			0.017	0.000	0.042	0.427
Model 7		-0.018	0.034				
	Sex			0.147	0.022	0.147	0.309
	Maturation			0.100	0.010	0.172	0.490
	Weight			-0.093	0.009	-0.170	0.519
	Limb Length			0.067	0.004	0.138	0.643
	LJ Vert Impulse (Ns)			-0.187	0.035	-0.217	0.192
Model 8		-0.049	0.005				
	Sex			0.111	0.012	0.110	0.444
	Maturation			0.096	0.009	0.167	0.508
	Weight			-0.168	0.028	-0.352	0.243
	Limb Length			0.066	0.004	0.138	0.648
	LJ Peak Vert Power (W)			0.074	0.005	0.108	0.609
Model 9		-0.013	0.039				
	Sex			0.131	0.017	0.129	0.363
	Maturation			0.156	0.024	0.278	0.280
	Weight			-0.033	0.001	-0.065	0.823
	Limb Length			0.053	0.003	0.108	0.716
	LJ Max Horiz. Force			-0.201	0.040	-0.337	0.162
Model 10		-0.054	0.001				
	Sex			0.113	0.013	0.113	0.435
	Maturation			0.108	0.012	0.190	0.457
	Weight			-0.139	0.019	-0.255	0.337
	Limb Length			0.060	0.004	0.125	0.679
	LJ Horiz. Impulse (Ns)			-0.033	0.001	-0.040	0.821
Model 11		-0.038	0.015				
	Sex			0.128	0.016	0.128	0.375
	Maturation			0.138	0.019	0.252	0.340
	Weight			-0.130	0.017	-0.233	0.367
	Limb Length			0.055	0.003	0.115	0.703
	LJ Peak Horiz Power (W)			-0.126	0.016	-0.157	0.383
Model 12		-0.055	0.008				
	Sex			0.145	0.021	0.150	0.340
	Maturation			0.037	0.001	0.059	0.810
	Weight			-0.151	0.023	-0.253	0.322
	Limb Length			0.084	0.007	0.168	0.585
	PA Score			-0.092	0.008	-0.096	0.547

Appendix F

Distal Tibia: Trabecular Number

	Independent Variables	Overall R2	R2 Change	partial r	Partial R2	Beta	p-value
Base		0.191					
	Sex			0.338	0.11	0.314	0.022
	Maturation			-0.200	0.04	-0.291	0.182
	Weight			0.325	0.11	0.491	0.028
	Limb Length			-0.238	0.06	-0.426	0.111
Model 1		0.159	0.000				
	Sex			0.324	0.10	0.329	0.014
	Maturation			-0.136	0.02	-0.218	0.342
	Weight			0.125	0.02	0.418	0.383
	Limb Length			-0.240	0.06	-0.480	0.090
	Muscle Area			0.023	0.00	0.056	0.873
Model 2		0.139	0.000				
	Sex			0.324	0.10	0.311	0.022
	Maturation			-0.155	0.02	-0.251	0.282
	Weight			0.159	0.03	0.564	0.271
	Limb Length			-0.238	0.06	-0.467	0.097
	CMJMax Force (N)			-0.022	0.00	-0.063	0.878
Model 3		0.163	0.022				
	Sex			0.294	0.09	0.277	0.038
	Maturation			-0.201	0.04	-0.337	0.161
	Weight			0.161	0.03	0.310	0.265
	Limb Length			-0.253	0.06	-0.488	0.076
	CMJ Impulse (Ns)			0.168	0.03	0.327	0.244
Model 4		0.165	0.023				
	Sex			0.283	0.08	0.268	0.047
	Maturation			-0.194	0.04	-0.317	0.177
	Weight			0.152	0.02	0.297	0.291
	Limb Length			-0.243	0.06	-0.465	0.089
	CMJ Peak Power			0.172	0.03	0.308	0.231
Model 5		0.190	0.046				
	Sex			0.244	0.06	0.232	0.087
	Maturation			-0.240	0.06	-0.410	0.093
	Weight			0.346	0.12	0.582	0.014
	Limb Length			-0.195	0.04	-0.370	0.176
	LJ Mean			0.243	0.06	0.247	0.089

Appendix F

	Distal Tibia: Trabecular Number						
	Independent Variables	Overall R2	R2 Change	partial r	Partial R2	Beta	p-value
Model 6		0.140	0.001				
	Sex			0.299	0.09	0.297	0.035
	Maturation			-0.145	0.02	-0.235	0.314
	Weight			0.225	0.05	0.552	0.116
	Limb Length			-0.237	0.06	-0.460	0.097
	LJ Vert Force (N)			-0.032	0.00	-0.070	0.824
Model 7		0.186	0.043				
	Sex			0.291	0.08	0.269	0.041
	Maturation			-0.151	0.02	-0.233	0.295
	Weight			0.229	0.05	0.380	0.110
	Limb Length			-0.251	0.06	-0.475	0.079
	LJ Vert Impulse (Ns)			0.234	0.05	0.244	0.102
Model 8		0.146	0.007				
	Sex			0.322	0.10	0.304	0.022
	Maturation			-0.163	0.03	-0.260	0.258
	Weight			0.212	0.04	0.404	0.140
	Limb Length			-0.230	0.05	-0.445	0.109
	LJ Peak Vert Power (W)			0.091	0.01	0.121	0.528
Model 9		0.184	0.041				
	Sex			0.315	0.10	0.291	0.026
	Maturation			-0.212	0.04	-0.344	0.139
	Weight			0.156	0.02	0.282	0.281
	Limb Length			-0.235	0.06	-0.443	0.101
	LJ Max Horiz. Force			0.229	0.05	0.346	0.110
Model 10		0.140	0.001				
	Sex			0.324	0.10	0.307	0.022
	Maturation			-0.147	0.02	-0.239	0.309
	Weight			0.296	0.09	0.510	0.037
	Limb Length			-0.237	0.06	-0.459	0.098
	LJ Horiz. Impulse (Ns)			-0.035	0.00	-0.039	0.807
Model 11		0.172	0.030				
	Sex			0.308	0.09	0.286	0.030
	Maturation			-0.207	0.04	-0.343	0.148
	Weight			0.268	0.07	0.440	0.060
	Limb Length			-0.235	0.06	-0.446	0.101
	LJ Peak Horiz Power (W)			0.195	0.04	0.219	0.175
Model 12		**0.244**	**0.064**				
	Sex			**0.269**	**0.07**	**0.242**	**0.074**
	Maturation			**-0.205**	**0.04**	**-0.286**	**0.176**
	Weight			**0.268**	**0.07**	**0.391**	**0.075**
	Limb Length			**-0.188**	**0.04**	**-0.324**	**0.217**
	PA Score			**0.295**	**0.09**	**0.271**	**0.049**

Appendix F

Distal Tibia: Trabecular Bone Volume Fraction

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.105					
	Sex			0.383	0.147	0.383	0.005
	Maturation			-0.025	0.001	-0.041	0.861
	Weight			0.127	0.016	0.210	0.374
	Limb Length			-0.164	0.027	-0.323	0.250
Model 1		0.088	0.003				
	Sex			0.362	0.131	0.365	0.009
	Maturation			-0.040	0.002	-0.067	0.779
	Weight			0.113	0.013	0.392	0.431
	Limb Length			-0.168	0.028	-0.343	0.240
	Muscle Area			-0.059	0.003	-0.150	0.683
Model 2		0.087	0.001				
	Sex			0.375	0.141	0.378	0.007
	Maturation			-0.018	0.000	-0.030	0.899
	Weight			0.029	0.001	0.103	0.844
	Limb Length			-0.157	0.025	-0.313	0.275
	CMJMax Force (N)			0.033	0.001	0.097	0.820
Model 3		0.113	0.025				
	Sex			0.354	0.125	0.351	0.012
	Maturation			-0.082	0.007	-0.139	0.571
	Weight			0.007	0.000	0.014	0.960
	Limb Length			-0.181	0.033	-0.353	0.209
	CMJ Impulse (Ns)			0.173	0.030	0.347	0.230
Model 4		0.102	0.014				
	Sex			0.350	0.123	0.352	0.013
	Maturation			-0.059	0.003	-0.098	0.684
	Weight			0.027	0.001	0.054	0.852
	Limb Length			-0.167	0.028	-0.327	0.245
	CMJ Peak Power			0.132	0.017	0.243	0.360
Model 5		0.222	0.050				
	Sex			0.306	0.094	0.304	0.031
	Maturation			-0.125	0.016	-0.215	0.389
	Weight			0.183	0.033	0.302	0.204
	Limb Length			-0.118	0.014	-0.229	0.413
	LJ Mean			0.247	0.061	0.258	0.084

Appendix F

Distal Tibia: Trabecular Bone Volume Fraction

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.086	0.000				
	Sex			0.367	0.135	0.385	0.009
	Maturation			-0.026	0.001	-0.042	0.860
	Weight			0.081	0.007	0.201	0.575
	Limb Length			-0.164	0.027	-0.323	0.255
	LJ Vert Force (N)			0.005	0.000	0.011	0.972
Model 7		0.086	0.000				
	Sex			0.377	0.142	0.381	0.007
	Maturation			-0.023	0.001	-0.040	0.864
	Weight			0.109	0.012	0.205	0.412
	Limb Length			-0.152	0.023	-0.324	0.254
	LJ Vert Impulse (Ns)			0.009	0.000	0.011	0.944
Model 8		0.110	0.022				
	Sex			0.382	0.146	0.377	0.006
	Maturation			-0.043	0.002	-0.069	0.768
	Weight			0.024	0.001	0.045	0.870
	Limb Length			-0.152	0.023	-0.295	0.293
	LJ Peak Vert Power (W)			0.162	0.026	0.045	0.262
Model 9		0.086	0.000				
	Sex			0.382	0.146	0.383	0.006
	Maturation			-0.024	0.001	-0.040	0.869
	Weight			0.111	0.012	0.211	0.444
	Limb Length			-0.164	0.027	-0.323	0.255
	LJ Max Horiz. Force			-0.001	0.000	-0.002	0.992
Model 10		0.091	0.005				
	Sex			0.383	0.147	0.382	0.006
	Maturation			-0.013	0.000	-0.021	0.929
	Weight			0.143	0.020	0.244	0.322
	Limb Length			-0.164	0.027	-0.321	0.256
	LJ Horiz. Impulse (Ns)			-0.076	0.006	-0.087	0.598
Model 11		0.087	0.001				
	Sex			0.378	0.143	0.379	0.007
	Maturation			-0.036	0.001	-0.061	0.805
	Weight			0.119	0.014	0.199	0.411
	Limb Length			-0.163	0.027	-0.320	0.259
	LJ Peak Horiz Power (W)			0.039	0.002	0.045	0.789
Model 12		0.193	0.030				
	Sex			0.392	0.154	0.381	0.008
	Maturation			-0.149	0.022	-0.212	0.328
	Weight			0.095	0.009	0.138	0.537
	Limb Length			-0.093	0.009	-0.163	0.545
	PA Score			0.200	0.040	0.185	0.188

Appendix F

Distal Tibia: BSIc

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.277					
	Sex			0.313	0.098	0.279	0.009
	Maturation			0.334	0.112	0.503	0.005
	Weight			0.286	0.082	0.411	0.017
	Limb Length			-0.289	0.084	-0.484	0.016
Model 1		0.307	0.005				
	Sex			0.270	0.073	0.230	0.020
	Maturation			0.325	0.106	0.518	0.005
	Weight			0.268	0.072	0.555	0.021
	Limb Length			-0.272	0.074	-0.471	0.019
	Muscle Area			-0.088	0.008	-0.138	0.454
Model 2		0.337	0.032				
	Sex			0.305	0.093	0.257	0.008
	Maturation			0.349	0.122	0.536	0.002
	Weight			-0.018	0.000	-0.045	0.879
	Limb Length			-0.239	0.057	-0.407	0.041
	CMJMax Force (N)			0.220	0.048	0.449	0.059
Model 3		0.303	0.000				
	Sex			0.288	0.083	0.249	0.013
	Maturation			0.328	0.108	0.547	0.004
	Weight			0.231	0.053	0.438	0.047
	Limb Length			-0.284	0.081	-0.493	0.014
	CMJ Impulse (Ns)			-0.008	0.000	-0.013	0.949
Model 4		0.304	0.001				
	Sex			0.282	0.080	0.243	0.015
	Maturation			0.318	0.101	0.522	0.006
	Weight			0.207	0.043	0.383	0.077
	Limb Length			-0.273	0.075	-0.477	0.019
	CMJ Peak Power			0.042	0.002	0.062	0.723
Model 5		0.338	0.033				
	Sex			0.241	0.058	0.204	0.039
	Maturation			0.250	0.063	0.403	0.032
	Weight			0.299	0.089	0.439	0.010
	Limb Length			-0.213	0.045	-0.370	0.068
	LJ Mean			0.224	0.050	0.200	0.055

Appendix F

Distal Tibia: BSIc

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.337	0.032				
	Sex			0.348	0.121	0.318	0.002
	Maturation			0.303	0.092	0.470	0.009
	Weight			0.050	0.003	0.101	0.617
	Limb Length			-0.286	0.082	-0.481	0.013
	LJ Vert Force (N)			0.222	0.049	0.419	0.057
Model 7		0.323	0.019				
	Sex			0.311	0.097	0.268	0.007
	Maturation			0.332	0.110	0.515	0.004
	Weight			0.308	0.095	0.463	0.008
	Limb Length			-0.252	0.064	-0.432	0.030
	LJ Vert Impulse (Ns)			-0.172	0.030	-0.156	0.144
Model 8		**0.357**	**0.051**				
	Sex			**0.304**	**0.092**	**0.252**	**0.008**
	Maturation			**0.333**	**0.111**	**0.504**	**0.004**
	Weight			**0.122**	**0.015**	**0.196**	**0.301**
	Limb Length			**-0.267**	**0.071**	**-0.442**	**0.022**
	LJ Peak Vert Power (W)			**0.279**	**0.078**	**0.317**	**0.016**
Model 9		0.319	0.015				
	Sex			0.280	0.078	0.238	0.016
	Maturation			0.289	0.084	0.465	0.013
	Weight			0.154	0.024	0.271	0.192
	Limb Length			-0.252	0.064	-0.435	0.030
	LJ Max Horiz. Force			0.154	0.024	0.216	0.192
Model 10		0.306	0.003				
	Sex			0.288	0.083	0.247	0.013
	Maturation			0.327	0.107	0.521	0.005
	Weight			0.242	0.059	0.388	0.038
	Limb Length			-0.275	0.076	-0.476	0.018
	LJ Horiz. Impulse (Ns)			0.068	0.005	0.072	0.565
Model 11		0.320	0.016				
	Sex			0.228	0.052	0.234	0.018
	Maturation			0.232	0.054	0.454	0.016
	Weight			0.190	0.036	0.355	0.047
	Limb Length			-0.204	0.042	-0.429	0.034
	LJ Peak Horiz Power (W)			0.127	0.016	0.164	0.180
Model 12		0.272	0.006				
	Sex			0.296	0.088	0.265	0.014
	Maturation			0.331	0.110	0.497	0.006
	Weight			0.270	0.073	0.390	0.026
	Limb Length			-0.274	0.075	-0.460	0.024
	PA Score			0.090	0.008	0.077	0.464

Appendix F

Tibia Shaft: Total Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.435					
	Sex			0.115	0.013	0.086	0.352
	Maturation			0.082	0.007	0.104	0.505
	Weight			0.366	0.134	0.479	0.002
	Limb Length			0.094	0.009	0.133	0.447
Model 1		**0.617**	**0.143**				
	Sex			**0.172**	**0.030**	**0.106**	**0.143**
	Maturation			**0.186**	**0.035**	**0.212**	**0.113**
	Weight			**-0.101**	**0.010**	**-0.150**	**0.394**
	Limb Length			**0.056**	**0.003**	**0.070**	**0.635**
	Muscle Area			**0.533**	**0.284**	**0.728**	**0.000**
Model 2		0.458	0.001				
	Sex			0.090	0.008	0.066	0.446
	Maturation			0.063	0.004	0.082	0.599
	Weight			0.184	0.034	0.429	0.119
	Limb Length			0.111	0.012	0.167	0.350
	CMJMax Force (N)			0.034	0.001	0.061	0.775
Model 3		**0.498**	**0.038**				
	Sex			**0.128**	**0.016**	**0.091**	**0.280**
	Maturation			**0.157**	**0.025**	**0.213**	**0.183**
	Weight			**0.442**	**0.195**	**0.774**	**0.000**
	Limb Length			**0.074**	**0.005**	**0.105**	**0.534**
	CMJ Impulse (Ns)			**-0.273**	**0.075**	**-0.339**	**0.020**
Model 4		0.480	0.020				
	Sex			0.117	0.014	0.084	0.325
	Maturation			0.125	0.016	0.170	0.292
	Weight			0.402	0.162	0.689	0.000
	Limb Length			0.065	0.004	0.095	0.584
	CMJ Peak Power			-0.200	0.040	-0.262	0.090
Model 5		0.463	0.005				
	Sex			0.111	0.012	0.083	0.352
	Maturation			0.097	0.009	0.137	0.416
	Weight			0.363	0.132	0.491	0.002
	Limb Length			0.070	0.005	0.107	0.556
	LJ Mean			-0.098	0.010	-0.078	0.407

Appendix F

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.458	0.000				
	Sex			0.078	0.006	0.061	0.511
	Maturation			0.065	0.004	0.086	0.588
	Weight			0.270	0.073	0.509	0.021
	Limb Length			0.106	0.011	0.155	0.373
	LJ Vert Force (N)			-0.012	0.000	-0.020	0.921
Model 7		0.458	0.000				
	Sex			0.086	0.007	0.063	0.467
	Maturation			0.064	0.004	0.084	0.590
	Weight			0.359	0.129	0.492	0.002
	Limb Length			0.102	0.010	0.153	0.390
	LJ Vert Impulse (Ns)			0.009	0.000	0.007	0.943
Model 8		0.467	0.008				
	Sex			0.091	0.008	0.066	0.442
	Maturation			0.052	0.003	0.067	0.664
	Weight			0.265	0.070	0.399	0.024
	Limb Length			0.120	0.014	0.175	0.312
	LJ Peak Vert Power (W)			0.128	0.016	0.128	0.281
Model 9		0.465	0.007				
	Sex			0.099	0.010	0.072	0.402
	Maturation			0.098	0.010	0.135	0.408
	Weight			0.361	0.130	0.602	0.002
	Limb Length			0.079	0.006	0.117	0.508
	LJ Max Horiz. Force			-0.118	0.014	-0.147	0.318
Model 10		**0.500**	**0.039**				
	Sex			**0.100**	**0.010**	**0.070**	**0.398**
	Maturation			**0.124**	**0.015**	**0.160**	**0.297**
	Weight			**0.438**	**0.192**	**0.644**	**0.000**
	Limb Length			**0.071**	**0.005**	**0.100**	**0.552**
	LJ Horiz. Impulse (Ns)			**-0.279**	**0.078**	**-0.261**	**0.017**
Model 11		0.465	0.006				
	Sex			0.102	0.010	0.074	0.392
	Maturation			0.099	0.010	0.138	0.406
	Weight			0.377	0.142	0.541	0.001
	Limb Length			0.078	0.006	0.116	0.514
	LJ Peak Horiz Power (W)			-0.111	0.012	-0.102	0.350
Model 12		0.437	0.009				
	Sex			0.140	0.020	0.107	0.259
	Maturation			0.088	0.008	0.110	0.479
	Weight			0.383	0.147	0.509	0.001
	Limb Length			0.071	0.005	0.102	0.566
	PA Score			-0.031	0.001	-0.101	0.285

Tibia Shaft: Total Area

Appendix F

Tibia Shaft: Cortical Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.668					
	Sex			0.096	0.009	0.055	0.438
	Maturation			0.060	0.004	0.057	0.630
	Weight			0.506	0.256	0.547	0.000
	Limb Length			0.241	0.058	0.269	0.048
Model 1		0.720	0.011				
	Sex			0.083	0.007	0.043	0.484
	Maturation			0.143	0.020	0.139	0.223
	Weight			0.273	0.075	0.361	0.019
	Limb Length			0.211	0.045	0.229	0.071
	Muscle Area			0.204	0.042	0.206	0.081
Model 2		**0.722**	**0.017**				
	Sex			**0.105**	**0.011**	**0.055**	**0.374**
	Maturation			**0.119**	**0.014**	**0.112**	**0.317**
	Weight			**0.120**	**0.014**	**0.198**	**0.313**
	Limb Length			**0.265**	**0.070**	**0.295**	**0.023**
	CMJMax Force (N)			**0.248**	**0.062**	**0.331**	**0.035**
Model 3		0.707	0.003				
	Sex			0.099	0.010	0.053	0.694
	Maturation			0.148	0.022	0.153	0.404
	Weight			0.459	0.211	0.620	0.212
	Limb Length			0.198	0.039	0.218	0.000
	CMJ Impulse (Ns)			-0.097	0.009	-0.105	0.093
Model 4		0.704	0.000				
	Sex			0.088	0.008	0.048	0.460
	Maturation			0.121	0.015	0.123	0.310
	Weight			0.426	0.181	0.558	0.000
	Limb Length			0.203	0.041	0.228	0.084
	CMJ Peak Power			-0.015	0.000	-0.015	0.897
Model 5		0.710	0.005				
	Sex			0.050	0.003	0.027	0.667
	Maturation			0.060	0.004	0.062	0.612
	Weight			0.510	0.260	0.549	0.000
	Limb Length			0.243	0.059	0.282	0.038
	LJ Mean			0.139	0.019	0.081	0.242

Appendix F

Tibia Shaft: Cortical Area

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.717	0.012				
	Sex			0.159	0.025	0.090	0.180
	Maturation			0.075	0.006	0.073	0.528
	Weight			0.255	0.065	0.364	0.030
	Limb Length			0.221	0.049	0.238	0.061
	LJ Vert Force (N)			0.209	0.044	0.258	0.075
Model 7		0.707	0.003				
	Sex			0.071	0.005	0.038	0.549
	Maturation			0.133	0.018	0.130	0.260
	Weight			0.493	0.243	0.533	0.000
	Limb Length			0.186	0.035	0.207	0.114
	LJ Vert Impulse (Ns)			0.109	0.012	0.065	0.360
Model 8		0.719	0.014				
	Sex			0.093	0.009	0.049	0.435
	Maturation			0.103	0.011	0.098	0.385
	Weight			0.373	0.139	0.424	0.001
	Limb Length			0.238	0.057	0.258	0.043
	LJ Peak Vert Power (W)			0.225	0.051	0.167	0.055
Model 9		0.707	0.003				
	Sex			0.078	0.006	0.042	0.512
	Maturation			0.086	0.007	0.088	0.469
	Weight			0.386	0.149	0.482	0.001
	Limb Length			0.226	0.051	0.254	0.055
	LJ Max Horiz. Force			0.095	0.009	0.088	0.423
Model 10		0.705	0.001				
	Sex			0.085	0.007	0.046	0.474
	Maturation			0.109	0.012	0.108	0.360
	Weight			0.459	0.211	0.525	0.000
	Limb Length			0.216	0.047	0.239	0.067
	LJ Horiz. Impulse (Ns)			0.053	0.003	0.037	0.654
Model 11		0.707	0.003				
	Sex			0.074	0.005	0.040	0.533
	Maturation			0.079	0.006	0.082	0.504
	Weight			0.464	0.215	0.515	0.000
	Limb Length			0.228	0.052	0.258	0.052
	LJ Peak Horiz Power (W)			0.101	0.010	0.069	0.395
Model 12		0.666	0.002				
	Sex			0.077	0.006	0.045	0.537
	Maturation			0.056	0.003	0.054	0.650
	Weight			0.491	0.241	0.532	0.000
	Limb Length			0.251	0.063	0.285	0.040
	PA Score			0.084	0.007	0.049	0.498

Appendix F

Tibia Shaft: Cortical Content

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.717					
	Sex			0.010	0.000	0.005	0.935
	Maturation			0.198	0.039	0.180	0.106
	Weight			0.563	0.317	0.587	0.000
	Limb Length			0.149	0.022	0.151	0.225
Model 1		0.757	0.001				
	Sex			-0.046	0.002	-0.023	0.695
	Maturation			0.214	0.046	0.195	0.067
	Weight			0.471	0.222	0.631	0.000
	Limb Length			0.152	0.023	0.152	0.196
	Muscle Area			-0.057	0.003	-0.052	0.632
Model 2		**0.775**	**0.020**				
	Sex			**0.006**	**0.000**	**0.003**	**0.960**
	Maturation			**0.247**	**0.061**	**0.214**	**0.035**
	Weight			**0.141**	**0.020**	**0.210**	**0.234**
	Limb Length			**0.196**	**0.038**	**0.192**	**0.097**
	CMJMax Force (N)			**0.294**	**0.086**	**0.358**	**0.012**
Model 3		0.754	0.000				
	Sex			-0.013	0.000	-0.006	0.912
	Maturation			0.230	0.053	0.222	0.050
	Weight			0.472	0.223	0.589	0.000
	Limb Length			0.124	0.015	0.124	0.295
	CMJ Impulse (Ns)			0.001	0.000	-0.001	0.995
Model 4		0.755	0.002				
	Sex			-0.025	0.001	-0.012	0.837
	Maturation			0.209	0.044	0.198	0.076
	Weight			0.444	0.197	0.534	0.000
	Limb Length			0.139	0.019	0.141	0.239
	CMJ Peak Power			0.082	0.007	0.072	0.490
Model 5		0.765	0.010				
	Sex			-0.068	0.005	-0.033	0.568
	Maturation			0.152	0.023	0.143	0.199
	Weight			0.578	0.334	0.592	0.000
	Limb Length			0.188	0.035	0.194	0.111
	LJ Mean			0.213	0.045	0.113	0.071

Appendix F

Tibia Shaft: Cortical Content

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		**0.777**	**0.022**				
	Sex			**0.105**	**0.011**	**0.053**	**0.375**
	Maturation			**0.183**	**0.033**	**0.160**	**0.121**
	Weight			**0.262**	**0.069**	**0.316**	**0.025**
	Limb Length			**0.141**	**0.020**	**0.133**	**0.235**
	LJ Vert Force (N)			**0.310**	**0.096**	**0.348**	**0.008**
Model 7		0.754	0.000				
	Sex			-0.014	0.000	-0.007	0.908
	Maturation			0.243	0.059	0.222	0.038
	Weight			0.563	0.317	0.588	0.000
	Limb Length			0.122	0.015	0.123	0.304
	LJ Vert Impulse (Ns)			0.004	0.000	0.002	0.972
Model 8		**0.767**	**0.013**				
	Sex			**-0.010**	**0.000**	**-0.005**	**0.936**
	Maturation			**0.229**	**0.052**	**0.202**	**0.052**
	Weight			**0.440**	**0.194**	**0.470**	**0.000**
	Limb Length			**0.154**	**0.024**	**0.149**	**0.194**
	LJ Peak Vert Power (W)			**0.238**	**0.057**	**0.161**	**0.043**
Model 9		**0.768**	**0.013**				
	Sex			**-0.036**	**0.001**	**-0.017**	**0.761**
	Maturation			**0.165**	**0.027**	**0.151**	**0.163**
	Weight			**0.395**	**0.156**	**0.440**	**0.001**
	Limb Length			**0.178**	**0.032**	**0.176**	**0.133**
	LJ Max Horiz. Force			**0.239**	**0.057**	**0.201**	**0.042**
Model 10		0.764	0.010				
	Sex			-0.020	0.000	-0.010	0.867
	Maturation			0.204	0.042	0.183	0.084
	Weight			0.491	0.241	0.513	0.000
	Limb Length			0.155	0.024	0.152	0.191
	LJ Horiz. Impulse (Ns)			0.208	0.043	0.131	0.078
Model 11		0.765	0.011				
	Sex			-0.040	0.002	-0.019	0.734
	Maturation			0.161	0.026	0.150	0.173
	Weight			0.514	0.264	0.527	0.000
	Limb Length			0.175	0.031	0.175	0.139
	LJ Peak Horiz Power (W)			0.215	0.046	0.133	0.068
Model 12		0.713	0.000				
	Sex			0.005	0.000	0.003	0.967
	Maturation			0.197	0.039	0.179	0.110
	Weight			0.554	0.307	0.583	0.000
	Limb Length			0.151	0.023	0.155	0.223
	PA Score			0.023	0.001	0.012	0.855

Appendix F

Tibia Shaft: Cortical Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.137					
	Sex			-0.165	0.027	-0.154	0.180
	Maturation			0.243	0.059	0.390	0.046
	Weight			0.172	0.030	0.263	0.160
	Limb Length			-0.155	0.024	-0.274	0.208
Model 1		**0.372**	**0.188**				
	Sex			**-0.283**	**0.080**	**-0.231**	**0.014**
	Maturation			**0.166**	**0.028**	**0.241**	**0.158**
	Weight			**0.483**	**0.233**	**1.049**	**0.000**
	Limb Length			**-0.109**	**0.012**	**-0.173**	**0.357**
	Muscle Area			**-0.493**	**0.243**	**-0.836**	**0.000**
Model 2		0.178	0.011				
	Sex			-0.189	0.036	-0.172	0.110
	Maturation			0.233	0.054	0.385	0.047
	Weight			0.008	0.000	0.022	0.949
	Limb Length			-0.121	0.015	-0.225	0.308
	CMJMax Force (N)			0.120	0.014	0.268	0.314
Model 3		0.198	0.030				
	Sex			-0.222	0.049	-0.202	0.059
	Maturation			0.160	0.026	0.274	0.176
	Weight			0.026	0.001	0.052	0.826
	Limb Length			-0.128	0.016	-0.230	0.281
	CMJ Impulse (Ns)			0.198	0.039	0.359	0.094
Model 4		0.202	0.034				
	Sex			-0.199	0.040	-0.204	0.056
	Maturation			0.145	0.021	0.279	0.162
	Weight			0.023	0.001	0.052	0.822
	Limb Length			-0.095	0.009	-0.198	0.357
	CMJ Peak Power			0.183	0.033	0.337	0.078
Model 5		0.202	0.034				
	Sex			-0.243	0.059	-0.227	0.038
	Maturation			0.144	0.021	0.250	0.223
	Weight			0.198	0.039	0.311	0.093
	Limb Length			-0.080	0.006	-0.150	0.499
	LJ Mean			0.208	0.043	203.000	0.078

Appendix F

Tibia Shaft: Cortical Density

	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.207	0.038				
	Sex			-0.107	0.011	-0.101	0.369
	Maturation			0.188	0.035	0.310	0.111
	Weight			-0.024	0.001	-0.052	0.841
	Limb Length			-0.148	0.022	-0.264	0.211
	LJ Vert Force (N)			0.221	0.049	0.457	0.060
Model 7		**0.228**	**0.058**				
	Sex			**-0.164**	**0.027**	**-0.145**	**0.167**
	Maturation			**0.214**	**0.046**	**0.343**	**0.069**
	Weight			**0.231**	**0.053**	**0.362**	**0.049**
	Limb Length			**-0.097**	**0.009**	**-0.173**	**0.742**
	LJ Vert Impulse (Ns)			**-0.273**	**0.075**	**-0.272**	**0.019**
Model 8		0.175	0.009				
	Sex			-0.194	0.038	-0.177	0.099
	Maturation			0.226	0.051	0.375	0.055
	Weight			0.114	0.013	0.208	0.335
	Limb Length			-0.140	0.020	-0.255	0.238
	LJ Peak Vert Power (W)			0.105	0.011	0.131	0.376
Model 9		**0.226**	**0.056**				
	Sex			**-0.225**	**0.051**	**-0.201**	**0.055**
	Maturation			**0.147**	**0.022**	**0.245**	**0.214**
	Weight			**-0.001**	**0.000**	**-0.001**	**0.996**
	Limb Length			**-0.094**	**0.009**	**-0.168**	**0.429**
	LJ Max Horiz. Force			**0.237**	**0.056**	**0.414**	**0.022**
Model 10		**0.226**	**0.056**				
	Sex			**-0.210**	**0.044**	**-0.186**	**0.075**
	Maturation			**0.185**	**0.034**	**0.299**	**0.118**
	Weight			**0.076**	**0.006**	**0.125**	**0.525**
	Limb Length			**-0.119**	**0.014**	**-0.210**	**0.317**
	LJ Horiz. Impulse (Ns)			**0.268**	**0.072**	**0.311**	**0.022**
Model 11		**0.211**	**0.042**				
	Sex			**-0.226**	**0.051**	**-0.204**	**0.054**
	Maturation			**0.147**	**0.022**	**0.249**	**0.216**
	Weight			**0.112**	**0.013**	**0.182**	**0.344**
	Limb Length			**-0.096**	**0.009**	**-0.174**	**0.420**
	LJ Peak Horiz Power (W)			**0.232**	**0.054**	**0.265**	**0.049**
Model 12		0.129	0.005				
	Sex			-0.146	0.021	-0.139	0.237
	Maturation			0.246	0.061	0.394	0.044
	Weight			0.183	0.033	0.284	0.138
	Limb Length			-0.165	0.027	-0.296	0.182
	PA Score			-0.076	0.006	-0.072	0.539

Appendix F

Tibia Shaft: SSIp							
	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Base		0.747					
	Sex			0.104	0.011	0.052	0.400
	Maturation			0.240	0.058	0.208	0.049
	Weight			0.613	0.376	0.632	0.000
	Limb Length			0.092	0.008	0.087	0.458
Model 1		**0.784**	**0.011**				
	Sex			**0.070**	**0.005**	**0.032**	**0.554**
	Maturation			**0.277**	**0.077**	**0.242**	**0.017**
	Weight			**0.375**	**0.141**	**0.451**	**0.001**
	Limb Length			**0.080**	**0.006**	**0.074**	**0.500**
	Muscle Area			**0.229**	**0.052**	**0.203**	**0.050**
Model 2		0.776	0.008				
	Sex			0.069	0.005	0.032	0.563
	Maturation			0.241	0.058	0.209	0.040
	Weight			0.260	0.068	0.395	0.027
	Limb Length			0.135	0.018	0.131	0.253
	CMJMax Force (N)			0.190	0.036	0.225	0.108
Model 3		0.772	0.005				
	Sex			0.075	0.006	0.035	0.529
	Maturation			0.276	0.076	0.258	0.018
	Weight			0.568	0.323	0.729	0.000
	Limb Length			0.075	0.006	0.071	0.531
	CMJ Impulse (Ns)			-0.144	0.021	-0.138	0.224
Model 4		0.768	0.001				
	Sex			0.062	0.004	0.030	0.601
	Maturation			0.246	0.061	0.228	0.036
	Weight			0.537	0.288	0.666	0.000
	Limb Length			0.080	0.006	0.078	0.501
	CMJ Peak Power			-0.053	0.003	-0.046	0.654
Model 5		0.772	0.004				
	Sex			0.021	0.000	0.010	0.863
	Maturation			0.178	0.032	0.166	0.132
	Weight			0.611	0.373	0.635	0.000
	Limb Length			0.130	0.017	0.131	0.273
	LJ Mean			0.132	0.017	0.068	0.265

Appendix F

Tibia Shaft: SSIp							
	Independent Variables	Overall R2	R2 Change	Partial r	Partial R2	Beta	p-value
Model 6		0.777	0.008				
	Sex			0.125	0.016	0.063	0.292
	Maturation			0.200	0.040	0.175	0.090
	Weight			0.370	0.137	0.465	0.001
	Limb Length			0.100	0.010	0.094	0.400
	LJ Vert Force (N)			0.197	0.039	0.215	0.095
Model 7		0.768	0.001				
	Sex			0.047	0.002	0.023	0.692
	Maturation			0.247	0.061	0.219	0.035
	Weight			0.599	0.359	0.626	0.000
	Limb Length			0.079	0.006	0.077	0.506
	LJ Vert Impulse (Ns)			0.057	0.003	0.030	0.629
Model 8		0.789	0.006				
	Sex			0.059	0.003	0.028	0.619
	Maturation			0.230	0.053	0.199	0.051
	Weight			0.503	0.253	0.550	0.000
	Limb Length			0.112	0.013	0.106	0.347
	LJ Peak Vert Power (W)			0.171	0.029	0.112	0.148
Model 9		0.774	0.006				
	Sex			0.041	0.002	0.019	0.733
	Maturation			0.183	0.033	0.166	0.121
	Weight			0.467	0.218	0.533	0.000
	Limb Length			0.127	0.016	0.124	0.284
	LJ Max Horiz. Force			0.165	0.027	0.135	0.163
Model 10		0.768	0.000				
	Sex			0.056	0.003	0.026	0.639
	Maturation			0.240	0.058	0.216	0.041
	Weight			0.577	0.333	0.637	0.000
	Limb Length			0.090	0.008	0.087	0.449
	LJ Horiz. Impulse (Ns)			-0.012	0.000	-0.008	0.917
Model 11		0.772	0.004				
	Sex			0.038	0.001	0.018	0.749
	Maturation			0.182	0.033	0.167	0.123
	Weight			0.565	0.319	0.593	0.000
	Limb Length			0.124	0.015	0.122	0.295
	LJ Peak Horiz Power (W)			0.143	0.020	0.086	0.229
Model 12		0.750	0.006				
	Sex			0.135	0.018	0.069	0.276
	Maturation			0.248	0.062	0.213	0.043
	Weight			0.626	0.392	0.656	0.000
	Limb Length			0.065	0.004	0.062	0.601
	PA Score			-0.159	0.025	-0.081	0.199